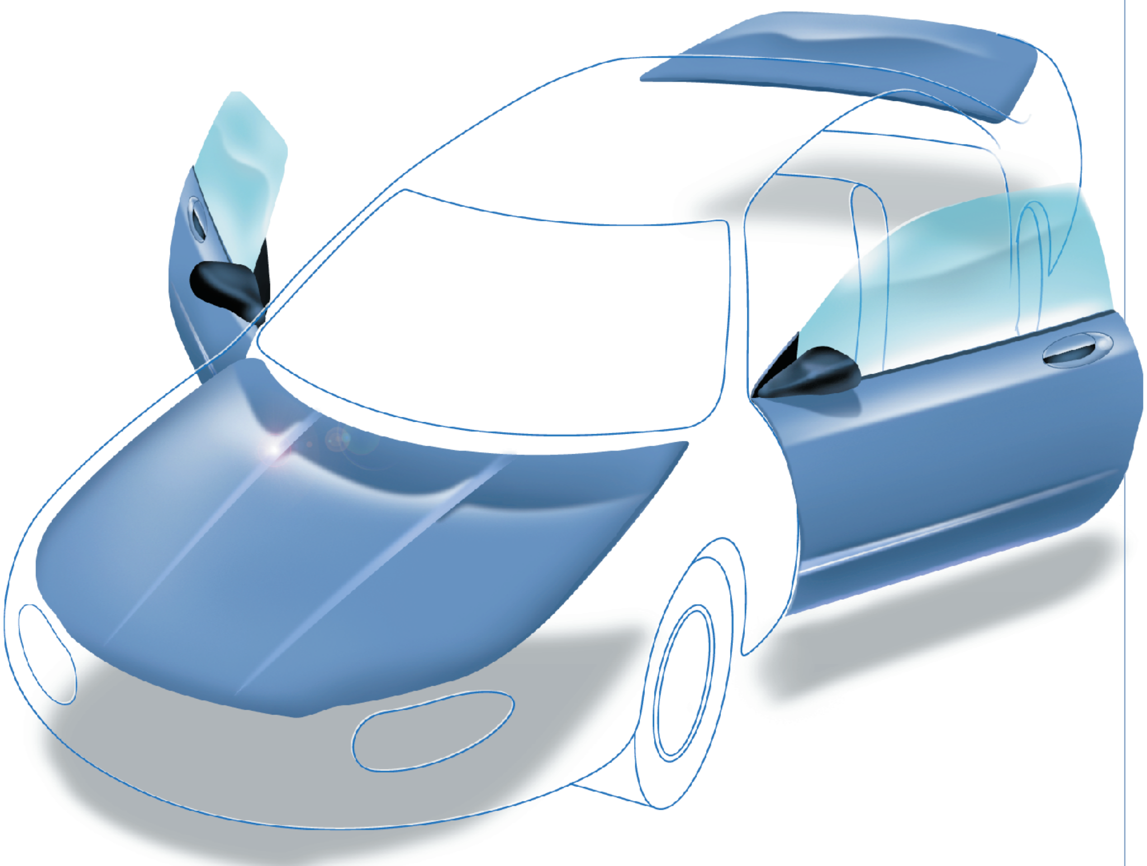
ULTRALIGHT STEEL AUTO CLOSURES



Engineering Report

April 2000

The design, materials, manufacturing, structural performance and economic analysis of the UltraLight Steel Auto Closures Program

Prepared by Porsche Engineering Services, Inc.

Porsche Engineering Services, Inc.

ULSAC Validation Program

Engineering Report
April 2000

to the

UltraLight Steel Auto Closures Consortium

PORSCHE
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Preface

Following the success of ULSAB in 1997, the ULSAC Consortium representing steel producers from all over the world was founded. Porsche Engineering Services, Inc. (PES) was commissioned to conduct a concept study for the development of UltraLight Steel Auto Closure concepts for all types automotive closures, that were structurally sound at affordable cost.

The results of this concept phase demonstrated that using steel as the material of choice in conjunction with the utilization of current and advanced manufacturing processes, could produce closures, which can achieve a 10% mass reduction, while maintaining structural performances at no cost penalty.

Encouraged by the results of the concept phase, the ULSAC Consortium once again commissioned PES to continue with the ULSAC Validation Phase. The ULSAC Consortium chose the Frameless Door Concept to be built and tested for validation. This concept design featured the most interesting technology with respect to parts manufacturing, assembly and the utilization of various steel grades and types. The Concept Phase design of the frameless door utilized the sheet hydroforming as an alternative to the conventional Stamping Process for the Panel Front Door Outer manufacturing, to improve dent resistance and oil canning performance and to reduce mass with reduced material thickness. Since no CAE tools are available to predict dent resistance and oil canning performance, the ULSAC Consortium decided to perform comparative testing on the frameless doors manufactured utilizing the stamping and sheet hydroforming manufacturing process for the Panel Front Door Outer with three material grades, in two material thickness' (0.06 mm and 0.07mm)

The Validation Phase began in November,1998. In spring 2000 the ULSAC DH door structures featuring stamped Door Outer Panels were built and tested for structural performance, dent resistance and oil canning. The tested doors show state-of-the-art structural performance compared to today's frameless door structures, and the mass reduction ranges from 22 to 42% compared to the normalized mass of benchmarked doors. In the Validation Phase a cost model was developed and the cost to produce the ULSAC frameless door structure was calculted. The results of this cost estimation show that the ULSAC door can be manufactured in high-volume production (225,000 +) with no cost penalty. The work to manufacture ULSAC door structures with sheet hydroformed Panel Front Door Outer is ongoing at this time. With the active sheet hydroforming process as the chosen method of manufacturing, no parts have yet been manufactured to date. The results of this work in progress will be published in a subsequent amendment to the ULSAC Engineering Report.

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1 Executive Summary

UltraLight Steel Auto Closure (ULSAC) Validation Phase

Background

On behalf of an International Consortium with 30 of the world's leading sheet steel producers, Porsche Engineering Services, Inc. (PES) in Troy, Michigan USA was responsible for program management, design and engineering, parts manufacturing, build of demonstration hardware (DH) and the economic analysis study for the UltraLight Steel Auto Closure Program (ULSAC).

Program Goals

The program goals are to define state-of-the-art closures, to develop lightweight steel closure concepts that are structurally sound at affordable cost and to build and test one selected closure concept representative for validation of all closure concepts developed in the Concept Phase.

Program Structure

In order to achieve these goals, the program was structured into two phases.

- Concept Phase – Paper Study
- Validation Phase – Build of Demonstration Hardware

Concept Phase Results

The Concept Phase ended in summer 1998. The findings of the Concept Phase demonstrated closure concepts for all types of closures: doors, hoods, decklids and hatches. These lightweight closures :

- Maintained structural performance
- Weighed up to 32% less than the average of benchmarked closures
- Weighed 10% less than best-in-class benchmarked
- Utilized current manufacturing and assembly processes and steel materials for manufacturing
- Could be built at no cost penalty

Validation Phase

The ULSAC Consortium selected the ULSAC Frameless Door Concept for validation. The Validation Phase began in November, 1998 and is still ongoing today. The overall goal was to validate the Concept Phase results by building the frameless door and testing it for structural performance. The program tasks in the Validation Phase were to manage the detail design engineering, CAE Analysis, design optimization for manufacturing and assembly, supplier selection for parts manufacturing and assembly, cost estimation and cost model development and to test and deliver the demonstration hardware to the ULSAC Consortium.

Door Package

Parallel with the start of the detail design, the Concept Phase package was refined. The ULSAC door package was updated with the changes made to the door structure concept design. These changes were mainly related to parts manufacturing feasibility, assembly process optimization, cost reduction and ultimately mass reduction. Package components such as window regulator, door latch and door handle were selected. The first choice was to select components from the Porsche Boxster/911. Alternatively "off-the-shelf" components with technology from automotive Tier One suppliers were considered. The ULSAC door package features a modular assembly approach integrating the components into main sub-modules for ease of assembly. The front door trim panel is made in the Stressed Skinned SandwichTechnology with the skins made of a light-weight Glass Matt Thermal Plastic (GMT) material, with a foam insert sandwiched between the skins providing panel stiffness which enhances passenger safety in side impact crashes. All components necessary to build a complete door are packaged and were considered in the design of the ULSAC door structure.

Design and Engineering

In the Validation Phase the design was focused on the refinement of the concept design for manufacturing and assembly, further mass reduction while keeping the structural performance and the optimization for manufacturing cost reduction. In the design process the Concept Phase design was optimized. The relatively complex hydroformed lower door frame was split into three separate parts allowing further mass reduction and the use of stock material ultra high strength steel

straight tubes which reduces cost for tooling and parts manufacturing. The major design changes occurred in the mirror flag area. The thin wall steel casting Bracket Front Door Remote Mirror was replaced with two stamped panels, although the casting was feasible to manufacture it was not cost efficient for mass production. The Panel Front Door Outer tailor-welded blank design for enhanced upper beltline stiffness was replaced with a standard stamped design.
This change was made possible with the introduction of the ultra high-strength steel Front Door Outer Belt Reinforcement Tube. This design change also reduced the parts manufacturing cost. The ULSAC door structure design has changed significantly in its transition from the Concept Phase into the Validation Phase and the door structure mass could be further reduced.

CAE Analysis

In the ULSAC Validation Phase CAE Analysis was used for support and guidance of the design and for prediction of structural performance. The CAE Analysis should ensure the ULSAC DH door structure would achieve similar structural performance as the analysis predicted for the concept door design. Two types of analysis were performed, Linear Analysis and Non-linear Analysis. In the Linear Analysis NASTRAN was used and the following load cases were considered:

Static Door Stiffness
- Vertical Sag Stiffness
- Upper Lateral Stiffness
- Lower Lateral Stiffness

Dynamic Door Stiffness
- Normal Modes

The Non-linear Analysis using LS-DYNA was performed for the following load cases:

- Quasi-static Side Intrusion
- Longitudinal Door Crush

The analysis results predicted that the ULSAC DH door structure would achieve the expected structural performance when tested. The longitudinal door crush analysis results show that the ULSAC DH door structure would considerably contribute to the enhancement of vehicle crash performance in frontal crashes.

Materials & Processes

The focus for the material selection was on production-ready materials and not on materials only available in the laboratory. The definition of the strength levels was the same as in the UltraLight Steel Auto Body (ULSAB) Program. In the ULSAB Program materials with a minimal yield strength of 140 MPa were defined as mild steel, materials with a minimum yield strength of 210 MPa and higher were defined as high-strength steel and materials with a minimum yield strength of greater than 550 MPa and higher were defined as ultra high-strength steel. The general requirements for the sheet steel materials were defined for the ULSAC program and included material thickness tolerances, coating type, coating thickness and coating tolerances. The requirements for the tubular hydroformed parts included material quality, dimension and tolerances, surface and welding process.

For the Panel Front Door Outer material selection, the program scope of work included the selection to be based on the results of comparative testing for dent resistance and oil canning. Two different forming processes, stamping and sheet hydroforming and three material grades in two thickness' (0.6mm and 0.7mm) were foreseen for the testing of the Panel Front Door Outer. For the tryout six grades of different types of materials in two thickness' each were delivered by ULSAC Consortium member companies. Panel Front Door Outers were successfully stamped with all materials in both thickness'. The final selection of the three materials for the build of eighteen test door structures for the comparative testing of dent resistance and oil canning was made by the ULSAC Consortium. The work to produce ULSAC Door Structures with Panel Front Door Outers utilizing the sheet hydroforming process is ongoing at the time of this report. The three selected materials for testing chosen by the ULSAC Consortium were BH210, BH260 and DP600. The front door latch and hinge tube both utilize the tubular hydroforming process for parts manufacturing. The difficult challenge was the latch tube manufacturing with the material thickness of 1.0 mm at an outside tube diameter of 48.0 mm combined with the small bending radius at the lower end of the tube.

Forming Simulations

In the ULSAC Program forming simulations for stamping and tubular hydroforming were performed. In general, forming simulations are performed to assess part manufacturing feasibility by calculating material thinning, strength conditions, and wrinkling that would exceed forming limit constraints. For the two tubular hydroformed parts, two types of forming simulation were performed: the one-step forming simulation and the incremental forming simulation. Currently, there is no completely accurate way to simulate the forming of these parts. The simulations were not used for tool development, but were done in parallel, or sometimes after the tool development had been completed. The time required to complete the simulations and lack of confidence in the results are issues that have limited the usefulness of the forming simulations for hydroformed parts. The forming simulations for the tubular hydroformed parts were performed in parallel to the tool and parts manufacturing. The incremental forming simulation correlated with the actual parts, and shows that this type of simulation is a useful tool, and can be used for future development of tubular hydroformed parts, prior to tool and parts manufacturing. All forming simulations for the stamped parts Panel Front Door Outer, Panel Mirror Flag Outer, Panel Front Door Inner Front and Panel Inner Rear predicted that all parts are feasible to manufacture and also correlated with the actual manufactured parts.

Parts Manufacturing

At the start of the detail design process in the Validation Phase suppliers for stamped and hydroformed parts were selected in order to be included in the simultaneous engineering process. This simultaneous engineering process allowed necessary changes prior to drawing release for tool design. PES and parts suppliers as well as representatives of steel companies worked together and all parts were manufactured successfully on time. The tooling for stamped parts are “soft” tools made of materials such as kirksite. Tools for tubular hydroforming are “hard” tools made of steel. The manufacturing of the stamped parts did not cause any problems and no design changes were necessary after the final drawing release. The first tryout of the hydroformed parts showed minor failures, and small design changes were made to make parts manufacturing feasible. Both tubular hydroformed parts could be successfully manufactured using axial force feeding to achieve higher forming limits at both ends of the parts.

DH Build

Porsche's Research and Design facility in Weissach, Germany was chosen for the assembly of the ULSAC DH. With the latest welding and assembly tools, alongside Porsche's qualified team of engineers and other specialists, the ULSAC DH door structure became a reality. For the assembly of the ULSAC door structure, four types of joining technologies were utilized. Laser welding was used to join the stamped parts of the door structure to the tubular hydroformed parts. Spot welding was used to join the Panel Mirror Flag Outer with the Panel Front Door Inner Front in the mirror flag area. Spot Welding was also used to join the Panel Front Door Outer with the Panel Front Door Inner Front and Panel Front Door Inner Rear on the lower inside overlap. Adhesive bonding was used in the hem flanges and between the lower tube and Panel Front Door Outer. Metal Arc Welding was used to join the Front Door Inner frame (hinge tube, latch tube, lower tube and outer belt reinforcement), bushings and the brackets for the window regulator attachment. To assemble the ULSAC DH a modular fixture system was used. The fixtures were developed in a CAD system and the positions of the locator holes were then incorporated into the parts of the design. The assembly of the door structure was performed in three steps:

- *Subassembly #1*: Joining of tubular parts, (Hinge Tube, Latch Tube, Lower Tube and Outer Belt Reinforcement and Hinge Bushings, the Regulator Attachment Brackets and Latch Reinforcement).

- *Subassembly #2*: Joining of Front Door Frame with the Front Door Inner Parts (Front Door Inner Front, Front Door Inner Rear, Mirror Flag Outer, and Latch Bushings).

- *Subassembly #3*: Bonding hem flanging and spot welding of Front Door Outer Panel with Subassembly #2.

For the ULSAC DH door structure assembly, assembly time and cost were reduced by combining virtual with actual assembly for the assembly process and fixture development.

Testing and Results

In the ULSAC Validation Phase, testing of the ULSAC DH door structure was undertaken to validate the design and to select the best-suited material for the Panel Front Door Outer manufacturing. Two types of testing were performed:

- Testing for structural performance
- Testing for dent resistance and oil canning

To better understand the structural performance of today's frameless state-of-the-art structure, benchmark testing was undertaken in respect to mass, vertical sag stiffness, upper and lower lateral stiffness and quasi-static side intrusion with the intention to compare the structural performance test results to the test results of the ULSAC DH door structure. The test results of the structural performance show that the ULSAC DH door structure achieves the desired structural performance. These results also show the ULSAC DH door structure falls below the target mass specification and has state-of-the-art structural performance when compared to the benchmarked frameless doors, at a significantly lower mass. With regards to safety, the ULSAC DH door structure test results show that the ULSAC design with two intrusion beams (part of the inner door structure) achieve comparable crush performance to the benchmarked doors. Quasi-static, dynamic and oil canning tests were performed on the ULSAC doors with different material qualities/grades. The ranking of the material grades/thickness in quasi-static and dynamic tests was very similar. Performance of the DP600 was the best, followed by BH260 and BH210. For the oil canning evaluation, which is related to material strength, DP600 performed worse than it did in the other tests. The best results for oil canning were achieved in BH260. The final material selection for the ULSAC Front Door Outer Panel was made by a group of experts including the steel supplier member companies and representatives of the ULSAC Consortium, testing companies and PES representatives. All test results were taken into consideration and BH260 has shown the best overall performance. Therefore, the final decision was to choose BH260 for the ULSAC DH Panel Front Door Outer manufacturing.

Economic Analysis

Part of the ULSAC program was to undertake an economic analysis to determine the manufacturing cost effective of the design solution. The objective was to establish a credible cost estimation for the ULSAC DH door structure using automotive practices of manufacturing engineering, process engineering, and cost estimating. Under the management of PES, and with support from the ULSAC Consortium members, an economic analysis group comprising of analysts from the Massachusetts Institute of Technology (MIT), Cameron Associates, Classic Design, Battle and Porsche AG (Germany), a Technical Cost Model program was developed to allow the possibility to analyze and compare existing or potential door structures to the ULSAC DH door structure. The results of this econmic analysis show that the additional cost for innovative manufacturing processes and assembly technologies such as hydroforming or laser welding as used the the ULSAC DH door structure are compensated by material cost savings. The results of this economic analysis in the ULSAC program show that the ULSAC DH door structure with significant mass reduction and at comparable performance to state-of-the-art generic doors can be built without cost penalty

2 Program Introduction

The ULSAC Consortium once again commissioned PES to continue with an ULSAC Validation Phase in the fall of 1998.

Background

In 1997, the UltraLight Steel Auto Closure (ULSAC) Consortium, representing thirty (30) international sheet steel producers, commissioned Porsche Engineering Services, Inc. (PES) to conduct a concept study on lightweight steel closures. In this Concept Phase the activities included benchmarking, target setting, concept designs and a cost estimation for all types of automotive closures.

The ULSAC Concept Phase findings demonstrated that the use of steel as the material of choice can produce closures, which at that point in time weighed 10% less than benchmarked best-in-class and maintained structural performance. The findings also showed that these closures could be fabricated using manufacturing processes and materials that were current and could be built with no cost penalty. The Concept Phase ended in the summer of 1998 with the release of the findings to the ULSAC Consortium.

Encouraged by the positive feedback the ULSAC Consortium once again commissioned PES to continue with an ULSAC Validation Phase in the fall of 1998.

2.1 Validation Phase Program Goal

The goal of the ULSAC Validation Phase is to validate the results and findings of the ULSAC Concept Phase and to build demonstration hardware of one selected closure type.

In the Concept Phase design concepts for all closure types have been developed and analyzed for structural performance and cost. The design of these closures did not include detail necessary for production and assembly.

In the Validation Phase, the ULSAC Consortium chose to build and test the frameless door structure as a demonstration example representative of all closure concepts developed in the Concept Phase.

Manufacturing processes utilized included tubular hydroforming, stamping, tailor welded blanks, laser- and spot welding.

The manufacturing of the ULSAC Concept Frameless door utilized processes such as:

- Tubular hydroforming
- Tailor welded blanks
- Stamping
- Laser welding
- Spot welding
- Bonding

2.2 Validation Design and Analysis

In the Validation Phase, detail design was undertaken, providing the data to build tooling and fixtures and to assemble demonstration hardware. The frameless door design is a refinement of the Concept Phase design. The final design is developed with the emphasis on mass reduction of more than 250,000 units/year. The intention was to continue the development of a "generic" door structure that took into consideration the manufacturing and assembly methods, build specification and final assembly sequence with the selected steel materials.

Computer Aided Engineering (CAE), continued in the Validation Phase in conjunction with the refinement of the design, provides results for structural performance. The CAE analysis provided confirmation of the design as well as structural performance. The CAE analysis in the Validation Phase includes:

- Finite Element Model Modification
- Structural Analysis consisting of:
  - Mass
  - Static Torsion (Upper and Lower)
  - Vertical Sag
  - Modal Analysis
  - Side intrusion performance

PES worked together with the ULSAC Consortium to achieve steel targets in steel for performance, timing and cost on the ULSAC DH.

2.3 Demonstration Hardware (DH)

The term demonstration hardware is used to emphasize that the closure structure is not a prototype but a legitimate representation of a production unit. The complete door structure was clear coat painted for unrestricted view of the build and construction methods. All demonstration hardware components are fully tooled (soft tools and hard tools for hydroforming). All demonstration hardware was built in a single-build sequence.

2.4 Scope of Work

Porsche Engineering Services, Inc. in Troy, Michigan, executed the program. The DH build was done at the Porsche AG R&D Center in Weissach, Germany. To achieve the targets for performance, timing and cost, PES program responsibilities included the following tasks:

- Program Management and Planning
- Build Management for the Construction of the Demonstration Hardware
- Build of Demonstration Hardware
- Part Supplier/Manufacturer Evaluation and Selection
- Component Structure Design and Engineering
- CAE Analysis
- Physical Testing
- Documentation of the manufacturing process
- Documentation of Dent Testing Results
- Documentation of Material Properties
- Economic Analysis
- Final Engineering Report

2.5 Materials

The ULSAC Consortium member companies provided all material-specific data required to design, develop and construct the ULSAC doors in the Validation Phase. ULSAC Consortium member companies, provided all materials used to manufacture parts for the ULSAC door to PES, including the tailor welded blanks and raw material (tubes) for manufacturing of the hydroform parts and the cross bars. In addition, the individual ULSAC member companies supported the program with data related to material selection and tailor welded blank development, as well as forming simulation on selected parts.

Structural performance testing, comparative dent testing and material testing performed on the ULSAC DH are presented in this Engineering Report.

2.6 Physical Testing

2.6.1 Structural Performances

Physical testing was undertaken to provide actual data and allow correlation with the CAE data with regards to the following:

- Mass
- Static Torsion (Upper and Lower)
- Vertical Sag

In addition to the original scope of work mentioned above, PES decided to perform side intrusion testing on frameless benchmarked doors and the ULSAC DH to compare their performances.

2.6.2 Comparative Testing for Dent Resistance and Oil Canning

Three steel companies conducted comparative testing for dent resistance and oil canning to select the best suited material and thickness to be used for demonstration hardware. Eighteen doors with stamped door outer panels were manufactured for statistical purposes in two material thickness' utilizing three different steel material grades. The results of the dent resistance testing at all three testing sites were documented. The ULSAC Consortium, together with PES, decided upon the final material thickness and grade used for the DH build.

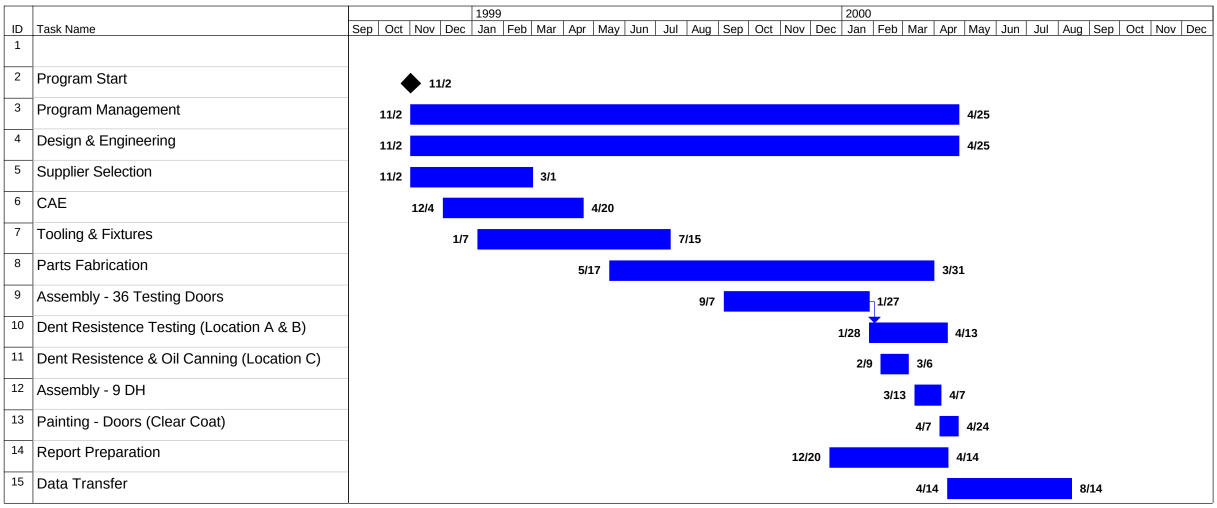
2.6.3 Material Testing

An independent laboratory analyzed and documented steel materials for part manufacturing with respect to their chemical composition, yield strength, tensile strength and elongation.

Prior to the beginning of the Validation Phase, the program timing was established and the various tasks assigned.

2.7 Program Timing

Prior to the beginning of the Validation Phase, program timing was established and the various tasks were assigned.



The Program started in November 1998 and was completed with the delivery of nine (9) DH door structures and part kits to the ULSAC Consortium in April 2000.

3 Package

The selection of package components was based on criteria such as mass, part design, and assembly process.

Background

Parallel with the detail design process in the ULSAC Validation Phase, the concept design package was refined.

The ULSAC door package was updated with the changes made to the door structure concept design. These changes were mainly related to optimization for parts manufacturing feasibility, assembly process, cost reduction and mass reduction.

The components selected for the door package were chosen and the part designs adjusted where necessary.

Another important factor in the packaging and design process was evaluation of the impact the selected components have on the final door assembly and assembly sequence.

3.1 Component Selection for the ULSAC Door Package

The ULSAC Program is focused on mass reduction of closure structures. The selection of the components and their impact for assembly and parts design had to be assessed prior to their implementation.

The following criteria were evaluated prior to final component selection for packaging of the ULSAC DH door structure.

- Mass of components
- Impact on door structure parts design & mass
- State-of-the-art technologies
- Modular design
- Suitable assembly process

During this process, the first choice for ULSAC DH package items were components from the Porsche 911/Boxster carline. Alternatively, "off-the-shelf" components with technology from automotive Tier One suppliers were considered.

Package components were carry-over parts from Porsche or "off-the-shelf" components of Tier One automotive suppliers.

3.1.1 Description of Selected Components

An exploded view of the ULSAC DH door structure with all package components is shown in Figure 3.1.1-1. The Parts List (Figure 3.1.1-2) identifies component name, supplier and the mass of the part.

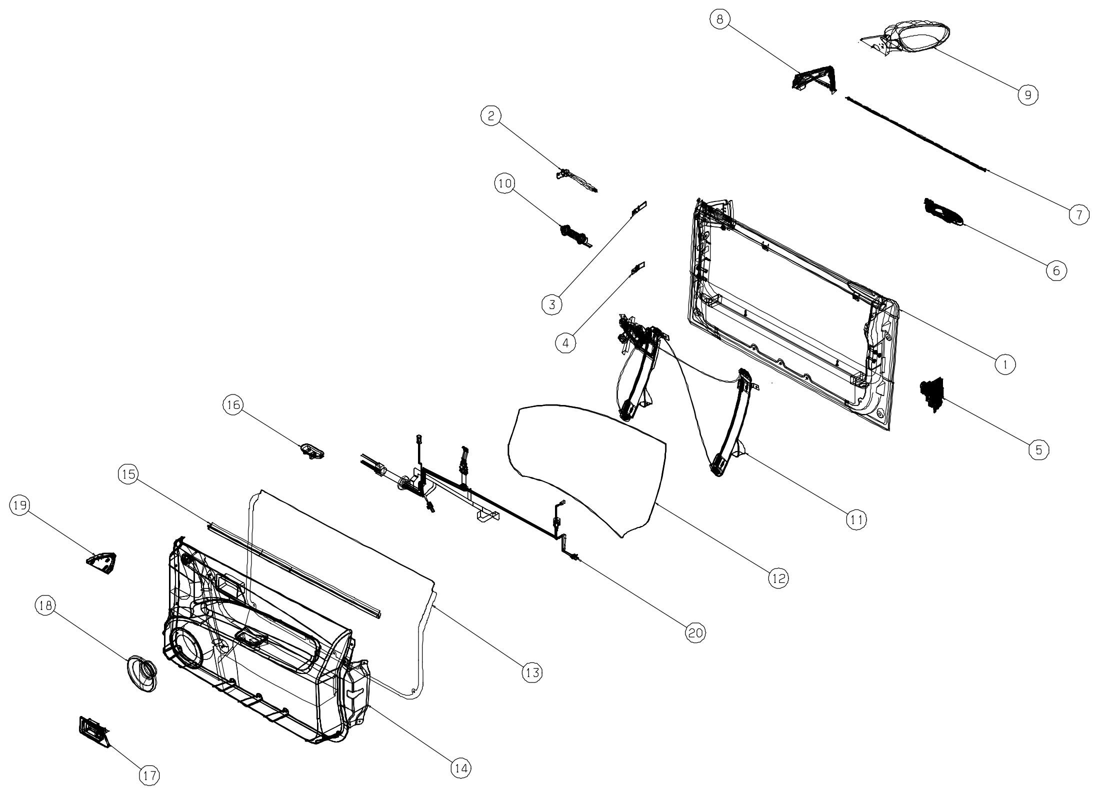


Figure 3.1.1-1 Exploded view ULSAC package

Item No.	Part No.	Name	Supplier	Est. Mass
1	3202	Final Assembly Front Door RH	PES	10.47
2	3126	Front Door Check Strap	Ford	0.41
3	3158	Front Door Bracket Trim Attachment - Upper	Lear	0.04
4	3156	Front Door Bracket Trim Attachment - Lower	Lear	0.04
5	3100	Front Door Latch Assembly	Delphi	0.37
6	3104	Front Door Outside Remote Handle	Porsche AG	0.47
7	3112	Front Door Outer Belt Seal	Ford	0.14
8	3110	Front Door Mirror Flag Seal	Porsche AG	0.14
9	3122	Front Door Mirror Assembly	Porsche AG	0.79
10	3140	Front Door Boot Harness	Delphi	0.04
11	3108	Front Door Window Regulator Assembly	Hi-Lex	1.91
12	3102	Front Door Glass	Quasar	3.76
13	3146	Front Door Vapor Barrier	XLO	0.17
14	3114	Front Door Trim Panel Assembly	Lear	2.63
15	3124	Front Door Inner Belt Seal	Porsche AG	0.29
16	3136	Front Door Switch Assembly	Delphi	0.04
17	3106	Front Door Inside Remote Handle	ITW-Deltar	0.08
18	3128	Front Door Speaker	Kenwood	0.56
19	3148	Front Door Mirror Flag Cover	Porsche AG	0.03
20	3138	Front Door Wire Harness Assembly	Delphi	0.30

Figure 3.1.1-2 Package components parts list

Both the mirror assembly and the outside remote handle were carry-over parts from the Porsche 911/Boxster cars..

3.1.1.1 Front Door Mirror Assembly Part # 3122

For the ULSAC Door the Porsche 911/Boxster Front Door Mirror was selected for package. The mirror features electric adjustment and mirror glass heating.

Figure 3.1.1.1-1 Porsche carry-over mirror

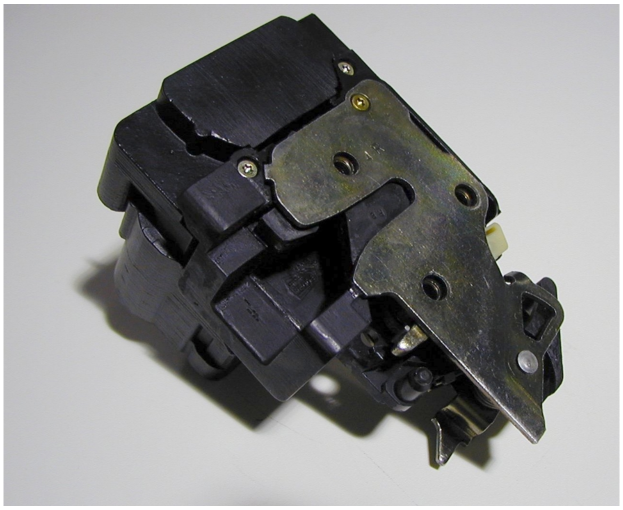
3.1.1.2 Front Door Outside Remote Handle Part # 3104

The ULSAC door handle is a carry-over part from the Porsche 911/ Boxster. The handle is used to activate the latch remotely. No mechanical linkage to the latch is necessary. This type of door handle has advantages for packaging and potential for mass reduction. The door handle also activates the window regulator motor to move the glass down. With this downward movement, the glass slides out of the seal located to the body structure in the upper door opening (which otherwise would be captured in the seal) and allows the door to be opened.

3.1.1.2-1 Porsche carry-over outside handle

The Delphi latch assembly was selected for its package size, high strength to mass ratio and overall feature ability.

3.1.1.3 Front Door Latch Assembly Part # 3100



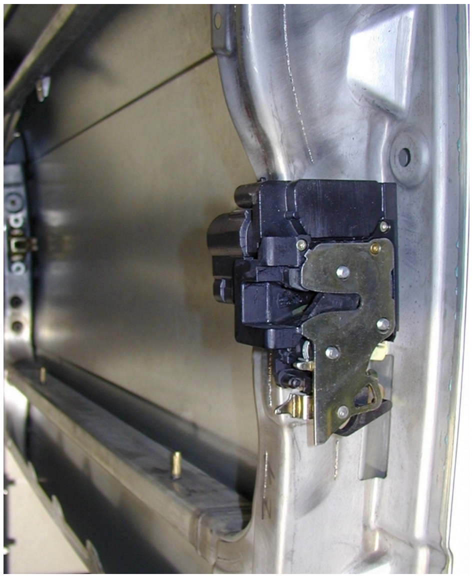
3.1.1.3-1 Front door latch assembly

A Tier One supplier company was chosen to supply the door latch. In a team approach with engineers from Delphi Interior Systems, the Delphi Mini Wedge Door Latch was selected for the ULSAC DH Front Door Latch Assembly. It was selected for its package size, high strength to mass ratio and overall feature ability.

The latch is electronically operated featuring Delphi's "E-Loc™ Electronic Locking" technology. The Electronic Locking" technology is the next step in expanding the use of electronics to improve the convenience of entering, exiting and utilizing vehicles. The system was validated and is in production today.

The Front Door Latch Assembly shown in Figure 3.1.1.3-1 was a prototype. Designed to meet the needs for the overall door assembly while harmonizing with the electrical, mechanical and trim architecture.

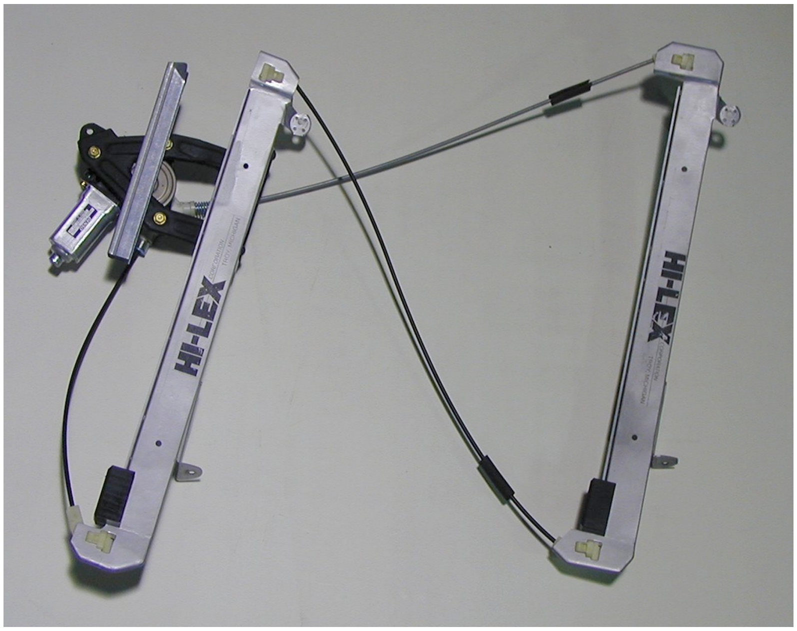
This latch system offers reduced assembly time in the Assembly plant, as well as logistic advantages from the fact that there are fewer items to ship. The latch mounted to the door structure is shown in Figure 3.1.1.3-2.



3.1.1.3-2 Front door latch assembly mounted to door structure

A dual channel drum & cable window regulator system was chosen for its maximized glass guidance characteristics.

3.1.1.4 Front Door Window Regulator Part # 3108



3.1.1.4-1 Front door window regulator part # 3108

A dual channel drum & cable window regulator system was chosen for its maximized glass guidance characteristics along with exceptional rotational stability for the ULSAC door package. The ULSAC Front Door Window Regulator was developed and prototyped by Hi-Lex Corporation, Troy, Michigan, in a simultaneous engineering approach with PES.

The door package required guide rails and a lift mechanism which would pass through a very small envelope to completely drop the glass within the door. This requirement was achieved through an unconventional cable routing and streamlined regulator design. A patented core wire technology allows to package in very tight locations without sacrificing long term durability performance.

The regulator is efficiently attached to the door structure. The window lift motor together with a lower glass guide channel is mounted to a bracket and placed in a location to minimize mass generated inertia that can be seen in door slam conditions, and still provides the critical attribute of lifting the glass at the rear edge.

The regulator is designed utilizing commonly found manufacturing techniques and can be built in a cost efficient manner.

The trim panel was designed to be a stiff high strength panel without adding mass compared to conventional systems.

3.1.1.5 Front Door Trim Panel Module

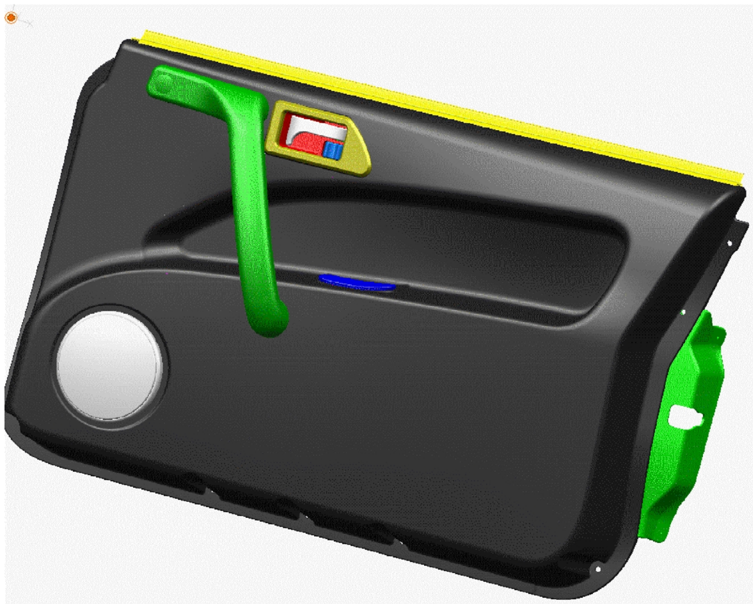


Figure 3.1.1.5-1 Front door trim panel module outside view

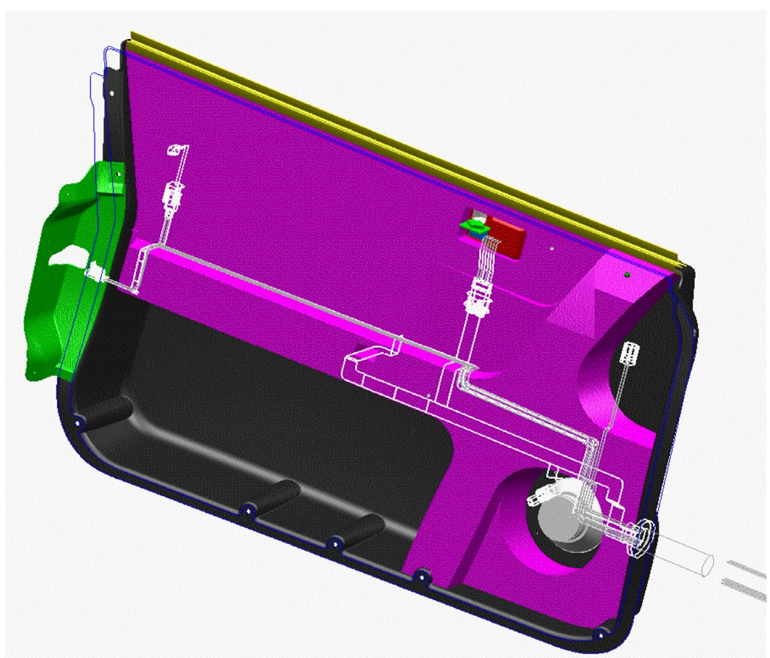


Figure 3.1.1.5-2 Front door trim panel module inside view

Lear engineers were consulted for their design layout, material selection and packaging components.

The Front Door Trim Panel was designed in collaboration with Lear Corporation, Southfield, Michigan, North American Lear Technology Center, engineers were consulted for design layout, selection of materials and packaging components. The goal was to design a trim module that could be easily assembled.

3.1.1.5.1 Front Door Trim Panel

The goal of the development of the door inner panel was to provide a stiff high impact strength panel without adding mass compared to conventional systems.

In general, today's door trim systems are composed of a cosmetic outer panel, a foam energy absorber, a structural inner panel and the sheet metal (door structure inner panel).

In a conventional design the decorative outer panel seldom takes any loading by itself and needs metal reinforcements to withstand the high pull strap and armrest loading (usually around 250 lbs force).

In order to reduce mass and to provide a stiff trim panel, the integration of functions is essential. Today, most panels already feature an energy absorbing foam block for side impact protection. The chosen design takes advantage of this and integrates the foam into the panel to provide safety and stiffness.

With the already existing compression molding process (Stressed Skinned Sandwich Technology), the preexisting foam structure is sandwiched between an outer and inner skin (see Figure 3.1.1.5.1-1). The skin is made of a lightweight GMT (Glass Matt Thermal Plastic) material.

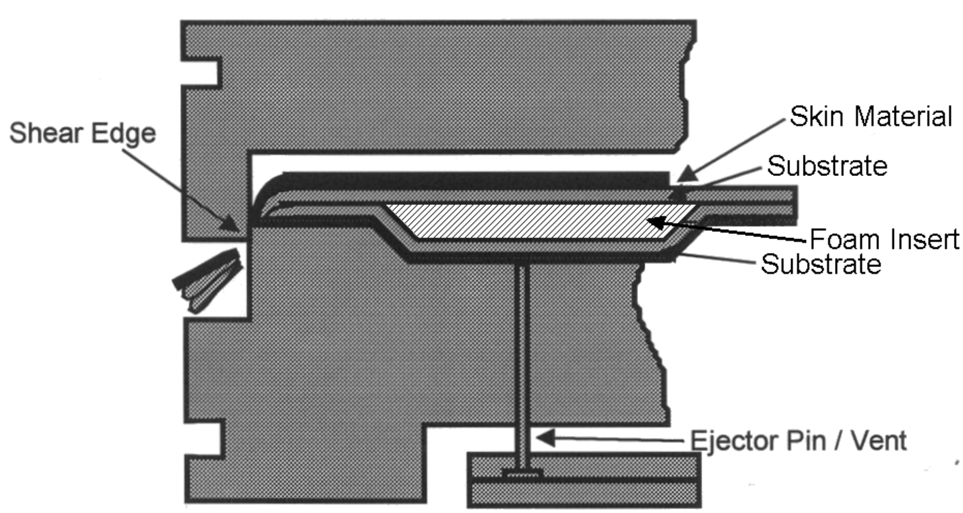


Figure 3.1.1.5.1-1 Compression molding process principal

The goal of the Front Door Trim Panel was to design a trim module that could be easily assembled.

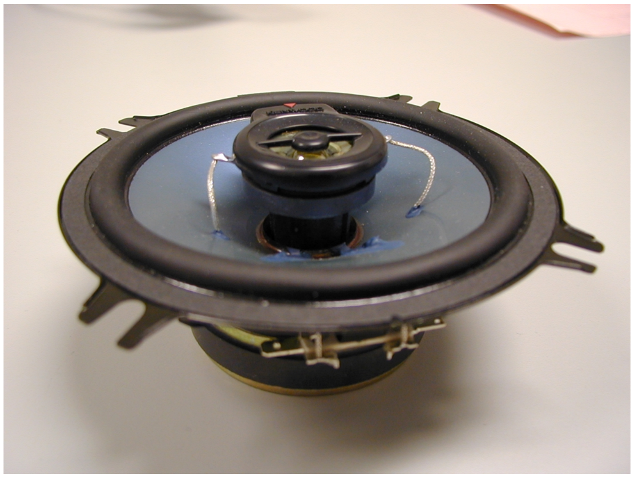
In Figure 3.1.1.5.1-2 the trim panel is shown with the inner foam structure.

Figure 3.1.1.5.1-2 Trim panel with inner foam structure

The Front Door Trim Panel was configured to fit several door trim components, creating the door trim module for the ULSAC door.

3.1.1.5.2 Front Door Trim Panel components

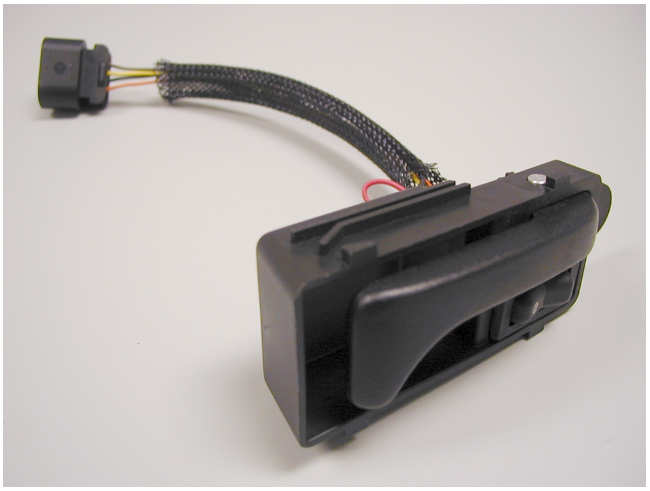
To configure the Front Door Trim Panel into a complete module, the following components were packaged.



Front Door Speaker Part # 3128

The Front Door Trim Panel provides enough stability to support the heavy speaker. The speaker and the speaker grille are assembled directly into the Front Door Trim Panel.

Figure 3.1.1.5.2-1 Front door speaker



Front Door Pull Handle Part # 3154

The interior Front Door Pull Handle packaged to the Front Door Trim is an “off the shelf” component from Lear Corporation product range. It activates the latch electrically, with no mechanical connection, in the same manner as the Front Door Outside Remote Handle does.

Figure 3.1.1.5.2-2 Front door pull handle

Carry-over parts from automotive manufactuers were used for components such as the switch assembly and the inner belt seal.

Front Door Switch Assembly Part # 3136

The door switch assembly is a carry-over part from DaimlerChrysler Corporation.

Figure 3.1.1.5.2-3 Front door switch assembly

Front Door Inner Belt Seal Part # 3124

The Front Door Inner Belt Seal is a modified carry-over part from the Porsche Boxster.

Figure 3.1.1.5.2-4 Front door inner belt seal

Front Door Mirror Flag Cover Part # 3148

The Front Door Mirror Flag Cover for the ULSAC door is shown in Figure 3.1.1.5.2-5 and the design is similar to the Porsche Boxster/ 911.

Figure 3.1.1.5.2-5 Front door mirror flag cover

Front Door Vapor Barrier Part # 3146

The Front Door Vapor Barrier is designed to seal the ULSAC door between structure and the Inner Trim Panel.

Figure 3.1.1.5.2-6 Frontdoor vapor barrier

Flexible printed circuit technology was chosen for its contribution to enhancing the modular build technique for the trim panel.

Front Door Wire Harness Assembly Part # 3138

Delphi Packard Electronic Systems developed the wiring harness for the ULSAC door. The flexible printed circuit (FPC) technology was chosen to be used for the ULSAC Door wiring harness.

FPC enhances the modular build technique of the Front Door Trim Panel Module. FPC also provides considerable mass reduction and the flat wires use less package space than traditional wiring methods.

The FCP wiring harness designed for the ULSAC Door Panel is shown in Figure 3.1.1.5.2–7.

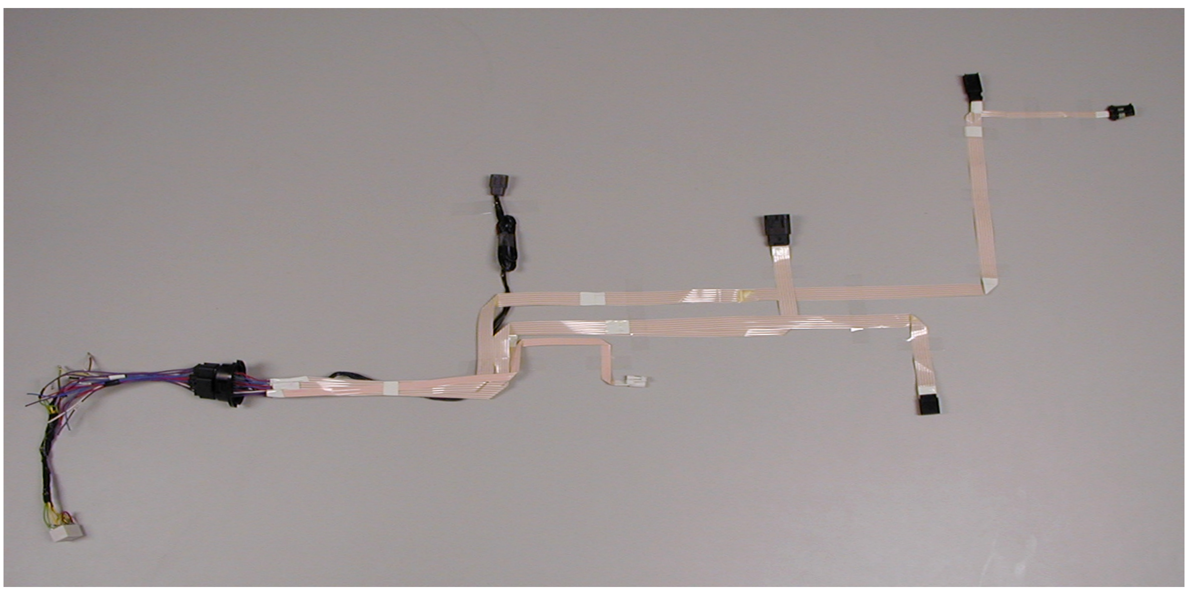


Figure 3.1.1.5.2-7 Front door wire harness assembly

3.1.1.6 Front Door Check Strap Part # 3126

The check strap packaged for the ULSAC DH door structure was a carry-over part from the Porsche cars (Boxster/911).

Carry-over parts from automotive manufacturers were used for package components such as the mirror flag seal and outer belt seal .

3.1.1.7 Sealing Components

Figure 3.1.1.7-1 Front door mirror flag seal

Front Door Mirror Flag Seal Part # 3110

The Front Door Mirror Flag Seal is a carry-over part from the Porsche Boxster/911.

Figure 3.1.1.7-2 Front door outer belt seal

Front Door Outer Belt Seal Part # 3112

The Front Door Outer Belt Seal is a carry-over part from the Ford Contour and slightly modified for assembly to the ULSAC Panel Front Door Outer.

Package components were assembled onto the ULSAC DH door structure in three steps.

3.2 Door Assembly

For the ULSAC frameless door, the assembly is based around three (3) subassembly modules:

- Door Structure Complete Module
- Window Regulator & Glass Module
- Door Inner Panel Module

The three (3) main subassembly modules are shown in Figure 3.2-1.

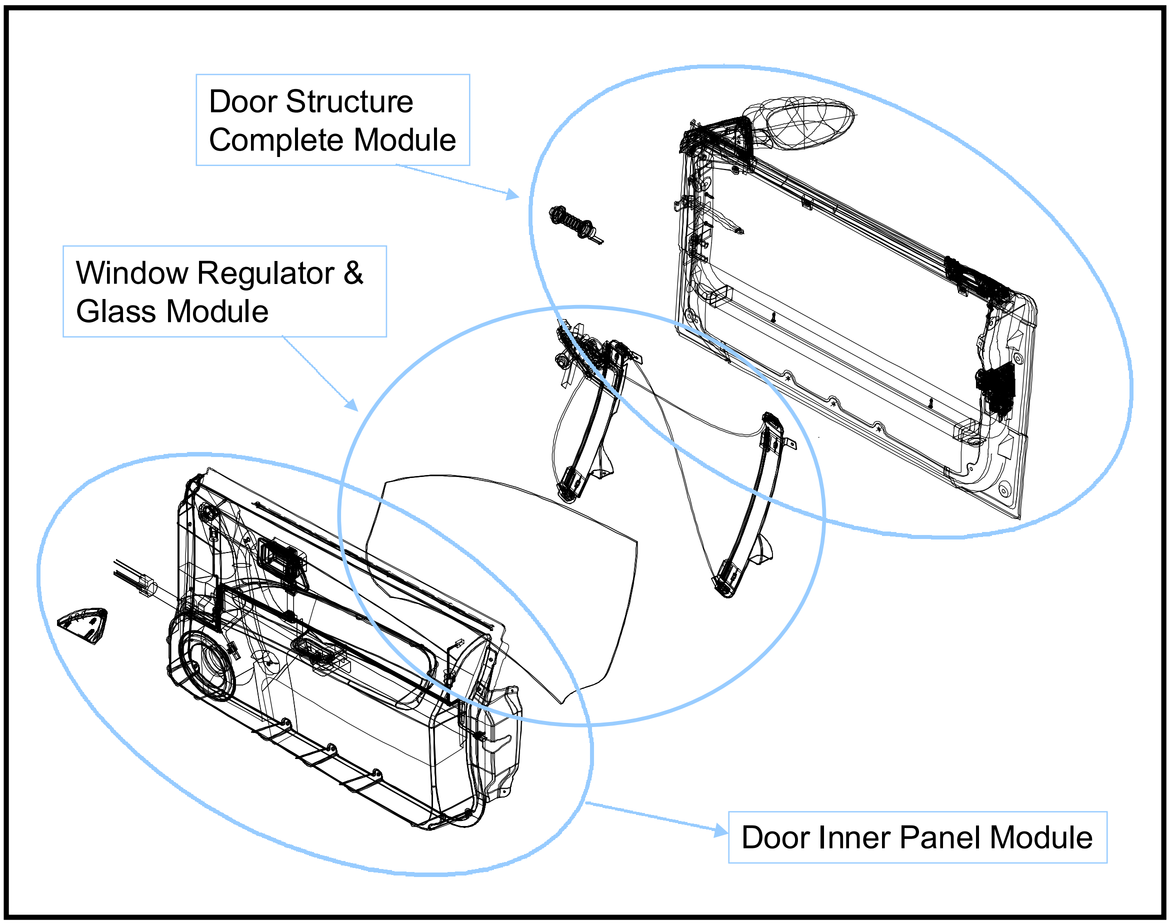


Figure 3.2-1 Door assembly - subassembly modules

3.2.1 Door Structure Module - Subassembly # 1

In this first subassembly of packaged components, the painted door structure is fit with the following components, shown in Figure 3.2.1-1.

1. Final Assembly Front Door RH Structure
2. Front Door Check Strap
3. Front Door Bracket Trim Attachment - Upper
4. Front Door Bracket Trim Attachment - Lower
5. Front Door Latch Assembly
6. Front Door Outside Remote Handle
7. Front Door Outer Belt Seal
8. Front Door Mirror Flag Seal
9. Front Door Mirror Assembly
10. Front Door Boot Harness

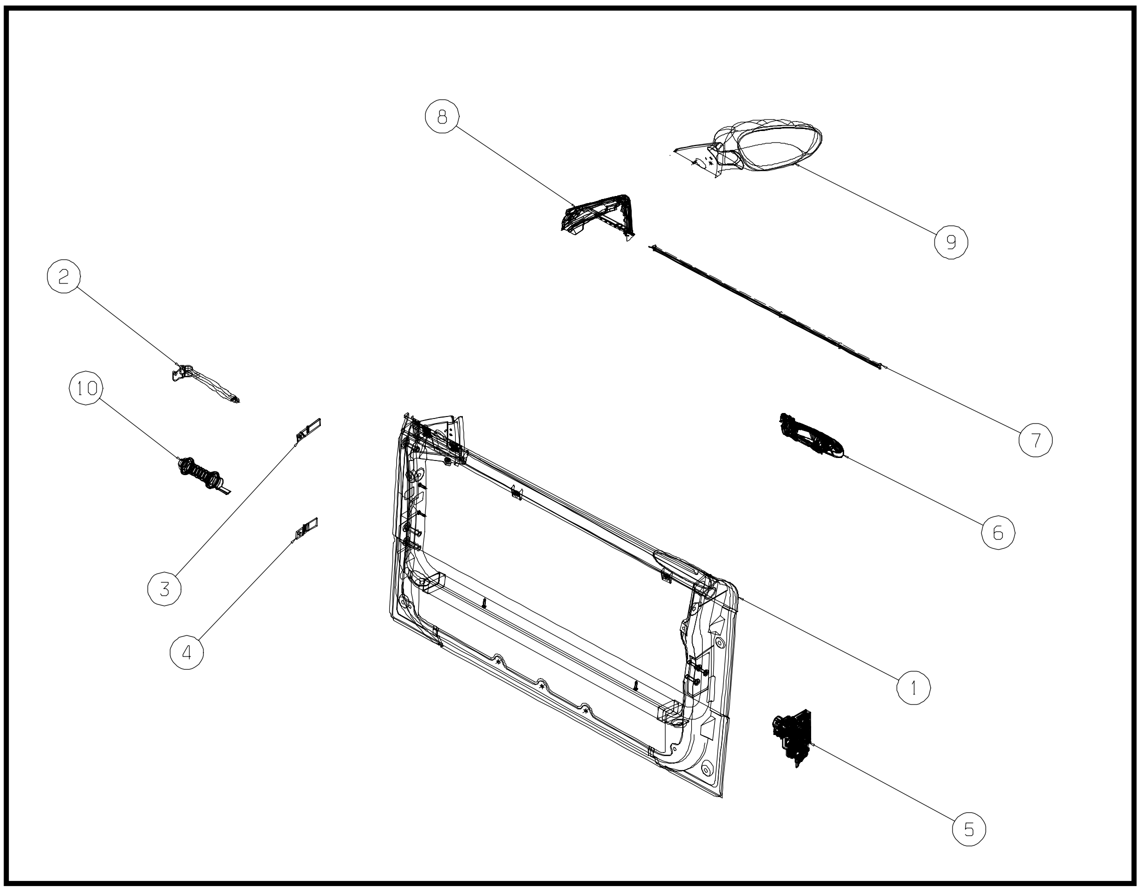


Figure 3.2.1-1 Subassembly #1

3.2.2 Door Structure Complete - Subassembly # 2

With the subassembly door structure module assembled, the window regulator is mounted into the door structure followed by the attachment of the glass, completing subassembly #2 (See Figure 3.2.2-1).

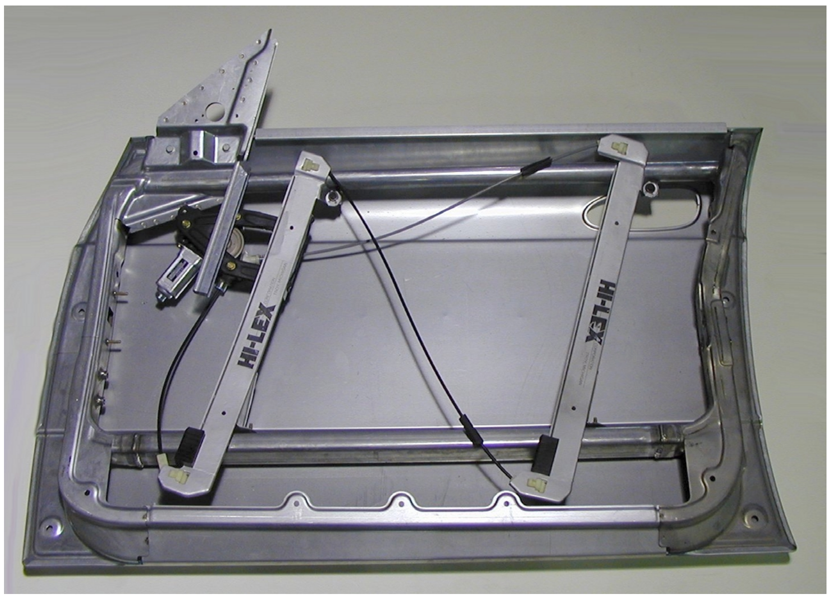


Figure 3.2.2-1 Subassembly #2 - door structure complete with window regulator

Figure 3.2.2-2 Subassembly #2 - door structure complete with window regulator & glass

In the final assembly step, the door is fitted with the vapor barrier and door inner trim panel module.

3.2.3 ULSAC Door Complete - Subassembly # 3

In the final assembly step, the door is fitted with the vapor barrier and the door inner trim panel module (see Figure 3.2.3-1).

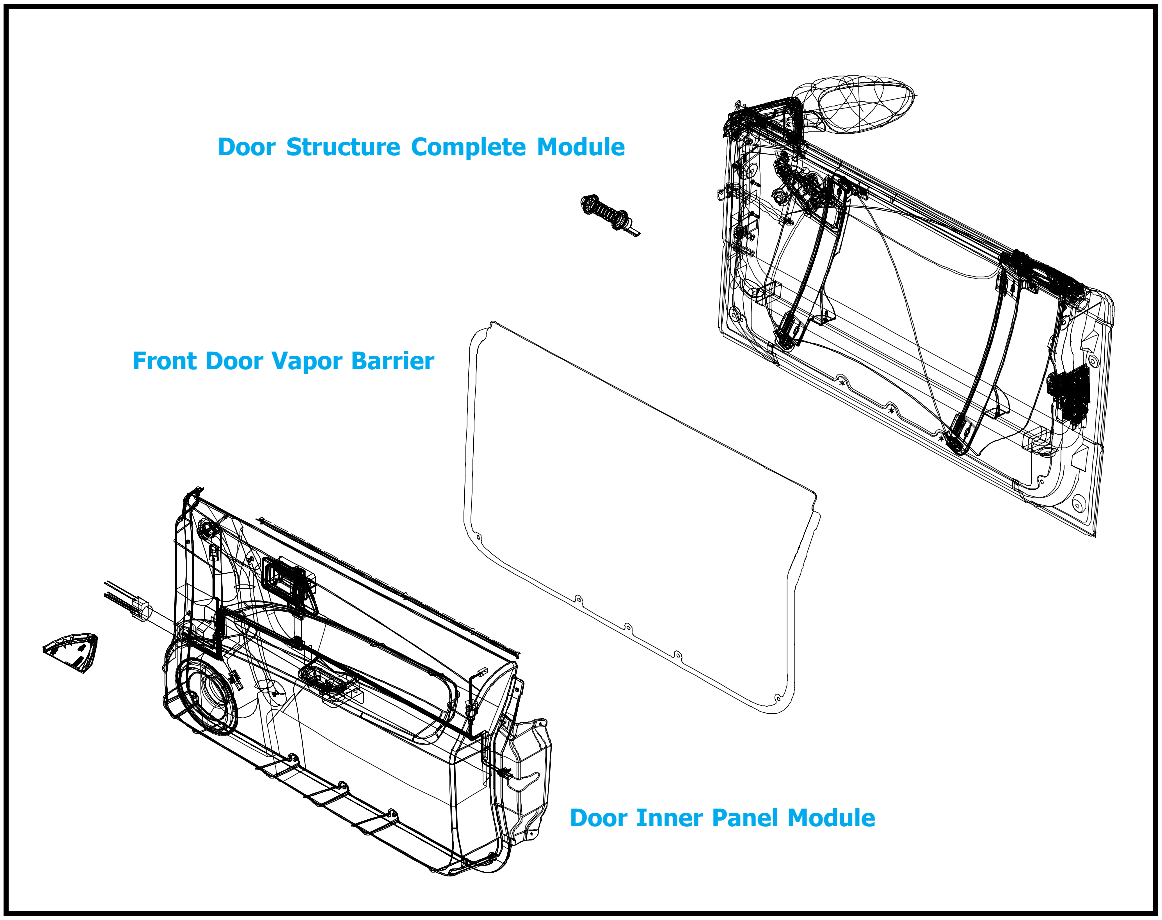


Figure 3.2.3-1 Subassembly - Door structure & Vapor barrier & Trim Panel Module

4 Design & Engineering

Background

The ULSAC Concept Phase findings provided concept design for all types of closures (doors, decklids, hoods and hatches), using steel as the material of choice. All concepts showed state-of-the-art performance at reduced mass at affordable cost.

In the Validation Phase, the design and engineering was focused on the refinement of the concept design for manufacturing and assembly maintaining, or further reducing, the door structure mass, while keeping the structural performance and manufacturing cost on the same level.

4.1 ULSAC Concept Phase Frameless Door Stucture Design

The exploded view shows (see Figure 4.1-1) the concept design of the frameless door development in the Concept Phase.

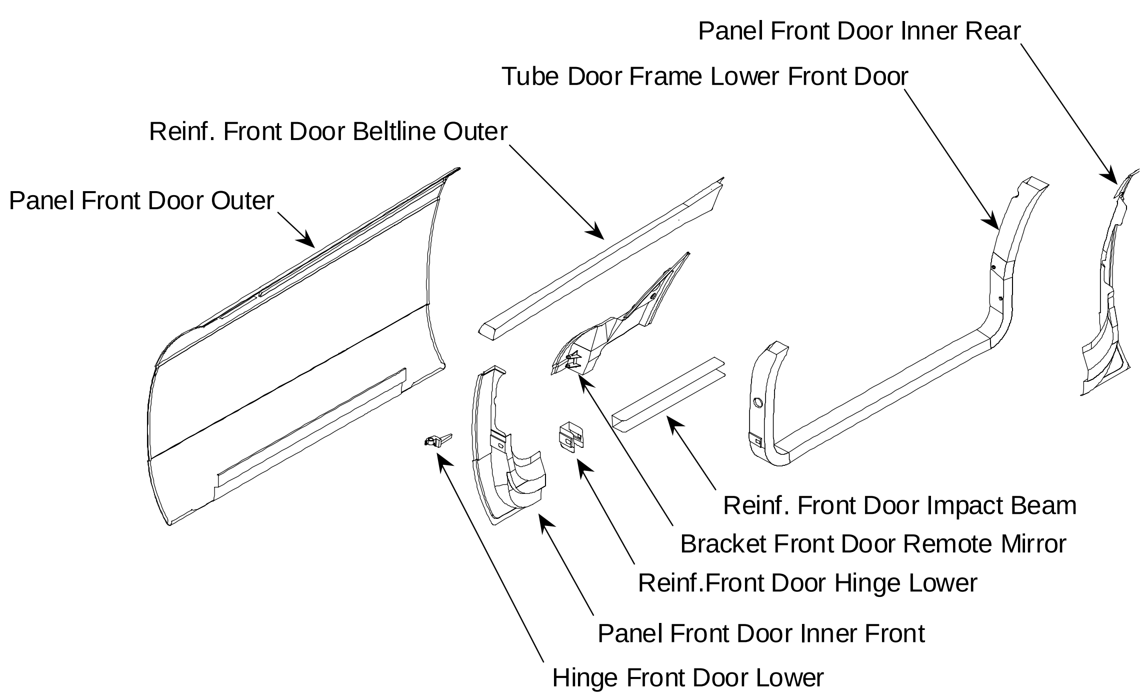


Figure 4.1-1 Exploded view ULSAC concept phase design

The design featured a hydroformed lower doorframe structure made of high strength steel material. The hydroformed lower doorframe with the reinforcement also functioned as side intrusion beam. The Bracket Front Remote Mirror incorporated the upper hinge and functioned as a structural node connecting the hydroformed Reinforcement Front Door Beltline Outer with the lower doorframe. The Panel Front Door Outer used a tailor welded blank layout for enhanced beltline stiffness. For the manufacturing process, the utilization of sheet hydroforming was anticipated. Assembly laser welding was specified for joining the Panel Front Door Inner Front and the Panel Front Door Inner Rear to the door inner frame. The Panel Front Door Outer was attached by hemming, to the panel Panel Front Door Inner Front and the Panel Front Door Inner Rear. The door structure concept design was based on the consideration to feature a window regulator module and a door inner panel module for the ULSAC door assembly, allowing better accessibility and service for the internal door components.

This design concept was calculated with a total mass of 11.47 kg and a normalized mass of 14.34 kg/m^2, 27% lighter than the benchmarked average (see Figure 4.1-2).

	Mass (kg)	Thickness (mm)	Grade (Mpa)	Manufacturing Process	Stock Material
Panel Front Door Outer	4.90	0.7/1.0	210	Sheet Hydroforming	Tailor Welded Blank
Panel Front Door Inner Front	0.38	0.6	140	Stamping	Coil
Panel Front Door Inner Rear	0.41	0.6	140	Stamping	Coil
Tube Door Frame Lower Front Door	3.21	1.2	280	Tube Hydroforming	Tube
Bracket Front Door Remote Mirror	0.87	1.5	140	Thinwall Cast	Ductile Iron
Reinforcement Front Door Beltline Outer	1.06	0.8	350	Tube Hydroforming	Tube
Reinforcement Front Door Impact Beam	0.40	1.0	1200	Rollformed	Coil
Reinforcement Front Door Hinge Lower	0.09	1.2	140	Stamping	Coil
Paint Allowence	0.15				
Total Mass	11.47				
True Surface (m^2)	0.80				
Normalized Mass (kg/m^2)	14.34				

Figure 4.1-2 Table of concept specifications

4.2 Frameless Door Structure design – Validation Phase

In the validation, each part of the Concept Phase was detailed. The simultaneous engineering process with our suppliers provided feedback with regards to manufacturing feasibility and cost, which resulted in design changes for part and changes in the assembly process.

4.2.1 Design Changes from Concept to Validation Phase

In our approach to optimize the Concept Phase design and the manufacturing, some of the design features changed and parts were substituted with alternative designs. The main area of redesign was in the front of the door structure with the cast Bracket Front Door Remote Mirror.

4.2.1.1 Bracket Front Door Remote Mirror

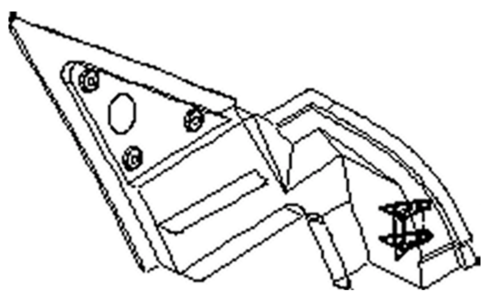


Figure 4.2.1.1-1 Bracket front door remote mirror

The Bracket Front Door Remote Mirror (see Figure 4.2.1.1-1) was designed as a thin wall casting utilizing ductile iron at 1.5 mm wall thickness. The objective of the approach was to integrate the attachment of the mirror, glass run channel and upper hinge into one (1) upper frame node. The CAE Analysis results showed that this casting contributes to improve structural performance and, by integrating multiple functions, to reduced door structure mass. In the assembly, laserwelding was foreseen to join the Bracket Front Door Remote Mirror with the Tube door Frame Lower Front Door and the Panel Front Door Inner Front.

In the Validation Phase, the ductile iron material, thin wall casting manufacturing process was analyzed for its part manufacturing feasibility and was determined that parts tolerances and the joining to the other door structure components, would not be sufficient for high volume production.

Alternatively, the utilization of the thin wall steel casting manufacturing process was investigated. In this process the part was feasible for manufacturing and assembly, but not cost efficient enough for mass production. As a result of this investigation, the concept design was revised and the cast Bracket Front Door Remote Mirror was substituted with two (2) stamped parts to reduce manufacturing cost for high volume production.

4.2.1.2 Panel Front Door Inner Front

To replace the mirror flag, the panel front door inner front (See Figure 4.2.1.2-1) was redesigned to combine the mirror flag area with the inner panel.

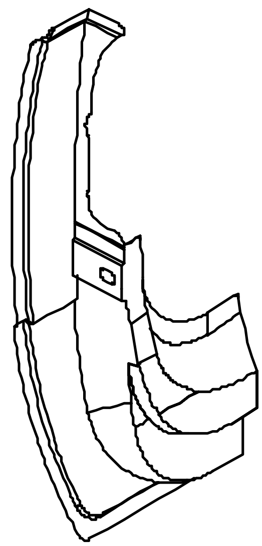


Figure 4.2.1.2-1 Panel front door inner front

4.2.1.3 Panel Front Door Outer

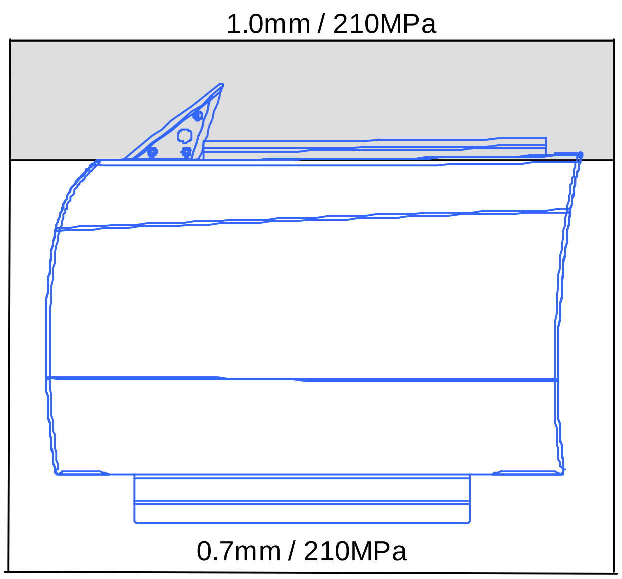
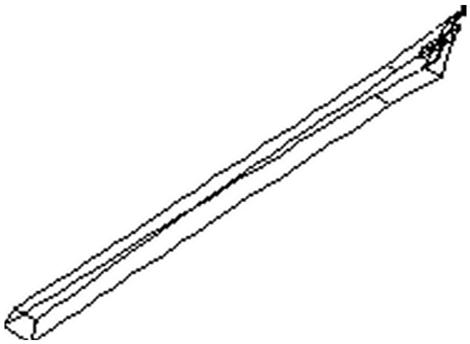


Figure 4.2.1.3-1 Door outer panel

The Panel Front Door Outer (See Figure 4.2.1.3-1) tailor welded blank design was replaced by a conventional blank layout. In the Concept Phase, this tailor welded blank layout provided additional beltline stiffness. The decision to use the sheet hydroforming process was replaced with the stamping process at this point in the Validation Phase.

4.2.1.4 Reinforcement Front Door Beltline Outer



The Concept Phase design featured a hydroformed tube, which was laserwelded to the rear upper vertical end of the Lower Doorframe and cast Bracket Front Door Remote Mirror. With the redesign of the Mirror Flag area in the Validation phase, the tubular hydroformed design was replaced by a straight ultra high strength steel tube.

Figure 4.2.1.4-1 Reinforcement front door beltline outer

4.2.2 Final Design Description

Figure 4.2.2-1 Final assembly front door (inside view)

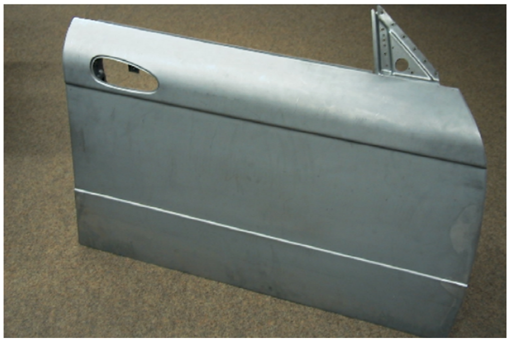


Figure 4.2.2-2 Final assembly front door (outside view)

The ULSAC DH door structure final design stage is shown in Figure 4.2.2-1 and Figure 4.2.2-2. The final design is a result of many iterations for optimization for mass and cost reduction, structural performance and assembly.

From the beginning of the Validation Phase, each design change was analyzed and resulted in further design optimizations or material substitutions until the design was satisfactory.

Forming simulations, parts manufacturer expertise, and the ULSAC Consortium members' knowledge of steel materials and their application possibilities supported the design team in parts manufacturing and material selection to make the best possible choices.

4.2.2.1 ULSAC Door Structure – Frame Design

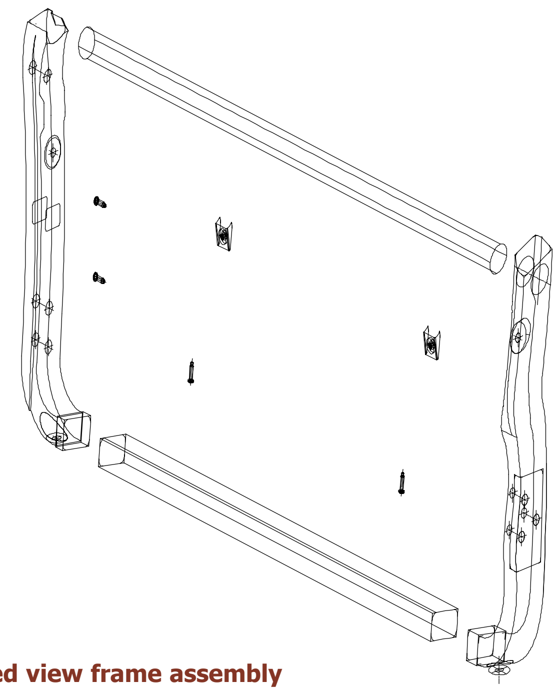


Figure 4.2.2.1-1 Exploded view frame assembly

In the Validation Phase, the doorframe was revised. The redesign is a result of approach taken to reduce manufacturing cost. In the final design, the one (1) piece lower doorframe from the Concept Phase design is split into three (3) elements.

By changing from one (1) relatively large hydroforming part into two (2) smaller hydroforming parts and a tubular part made of stock material reduced the tooling cost. Furthermore and most important, it allowed different diameter and material thicknesses for the Front Hinge Tube, the Rear Latch Tube and the Front Door Lower Tube.

In the design process, also considered was the possibility to use tailored tubing, for the Lower Frame design. Tailored tubing with various material thicknesses and material grades might be a manufacturing process for future developments. Questions in regard to prebending and preforming feasible combinations of steel grades and material thicknesses in the tailored tube process need to be answered prior to developing any manufacturing - feasible design. For this reason, this Program did not investigate further using a one (1) piece tailored tube frame.

4.2.2.1.1 Latch Tube Design

The hydroformed Latch Tube (See Figure 4.2.2.1.1-1) material thickness was reduced to 1.0 mm from 1.2 mm compared to the concept design Lower Doorframe. This reduction in material thickness lowered the mass, but made it necessary to add a local reinforcement at the latch area to provide the strength needed for side impact intrusion.

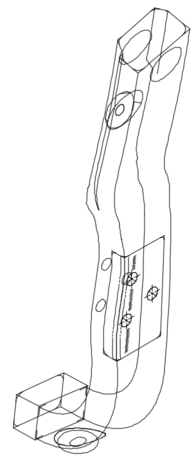


Figure 4.2.2.1.1-1 Hydroformed latch tube

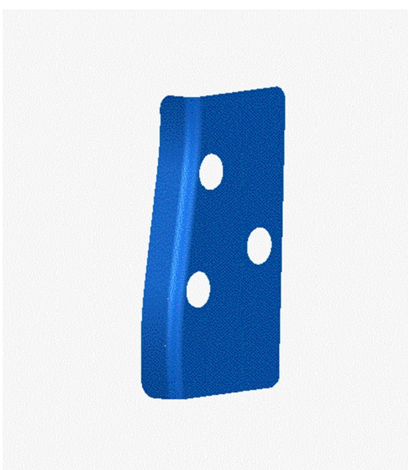


Figure 4.2.2.1.1-2 Latch reinforcement

The Latch Reinforcement (See Figure 4.2.2.1.1-2) is made from a 1.2 mm 140 MPa yield strength material and laser welded to the Latch Tube. For the same reasons as mentioned earlier, the use of tailored tubing to eliminate the need for this reinforcement was not pursued.

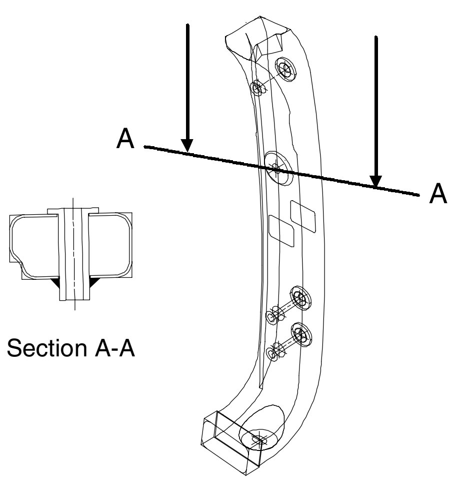
The lower end of the Latch Tube is designed to accommodate the Front Door Lower Tube. In the frame assembly, the Lower Tube is slotted into the Latch Tube and MAG welded.

4.2.2.1.2 Front Door Hinge Tube

The hydroformed Front Door Hinge Tube (See figure 4.2.2.1.2-1) material thickness was kept at 1.2 mm with the yield strength of 280 MPa.

Figure 4.2.2.1.2-1 Front door hinge tube

The lower end of the Latch Tube is designed to accommodate the Front Door Lower Tube. In the frame assembly, the Lower Tube is slotted into the Hinge Tube and MAG welded.



For the attachment of the Upper and Lower Hinges, three (3) bushings are welded through to the Hinge Tube: One (1) for the upper and two (2) for the lower hinge. The bushing heads are laserwelded to the outside of the frame and MAG welding on the inside. The weld through bushings provides the possibility to attach the Hinge and function as bulkheads inside the tube (See Figure 4.2.2.1.2-2). They stabilize the tube section under load transferred from the hinges.

Figure 4.2.2.1.2-2 Hinge bushings installed

4.2.2.1.3 #3010 Front Door Lower Tube Design

The Front Door Lower Tube (See Figure 4.2.2.1.3-1) is designed using a straight rectangular ultra high strength steel standard stock tube with material thickness of 1.6 mm and a yield strength of 650 MPa. It replaced the middle section of the ULSAC Concept Phase design made of a 1.2 mm high strength steel material with yield strength of 350 MPa and eliminated the rollformed impact beam reinforcement designed of a 1.0 mm ultra high strength steel material with 1200 MPa yield strength.

The elimination of the rollformed reinforcement saves costs for parts manufacturing, tooling and in the assembly with reduced welding.

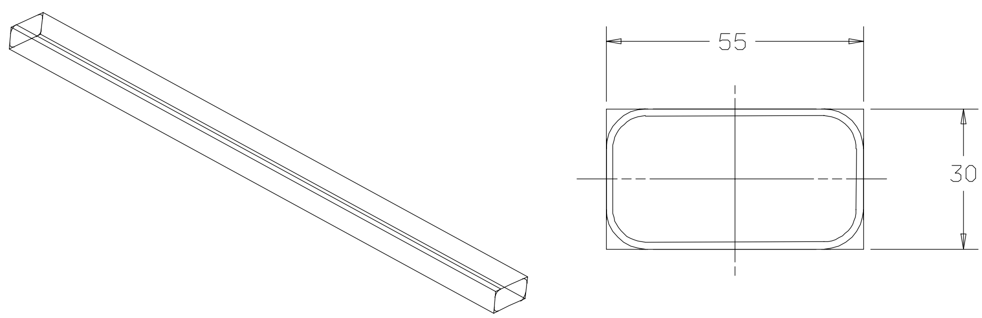


Figure 4.2.2.1.3-1 Front door lower tube design

4.2.2.1.4 # 3016 Outer Belt Reinforcement Design

As a result of the design changes in the Mirror Flag area, the hydroformed Outer Belt Reinforcement was revised for the possibility to further reduce mass and manufacturing cost.

In the final ULSAC design, the tubular hydroformed Outer Belt Reinforcement at a material thickness of 1.2 mm and a yield strength of 350 MPa is replaced by a straight 1.0 mm standard stock material ultra high strength steel tube with 650 MPa yield strength (See Figure 4.2.2.1.4-1).

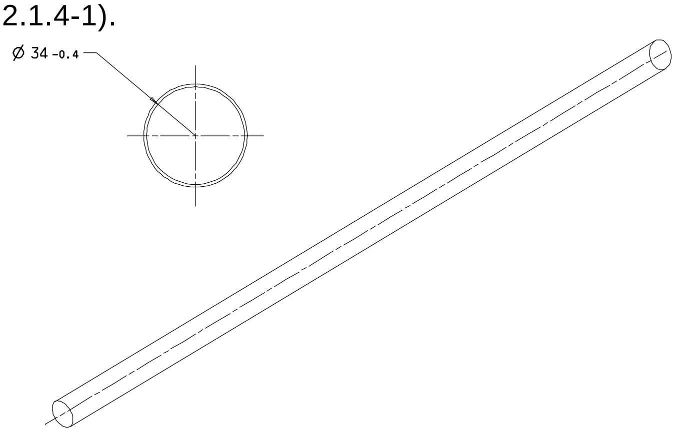


Figure 4.2.2.1.4-1 Outer belt reinforcement design

The reduction from 1.2 mm material thickness to 1.0 mm could be made without sacrificing the structural integrity of the door structure. Using this ultra high strength steel tube also enhances the side impact crush resistance of the door structure by functioning as a second intrusion beam in conjunction with the lower beam.

The use of a straight tube from stock material instead of a tubular hydroformed part has reduced part cost and eliminated the cost for a hydroformed tool.

4.2.2.1.5 Frame Assembly

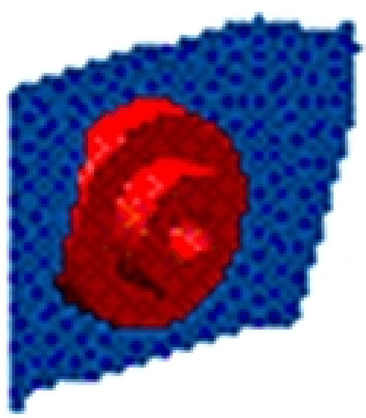


Figure 4.2.2.1.5-1 Clinch nuts

The frame is designed to be assembled using MAG welding for joining of Latch, Hinge, Upper and Lower Tube. The studs and the brackets to attach the Window Regulator and the check straps to the door structure in the final door assembly are also welded in the frame assembly station (See Chapter 9 DH Build). The Two (2) Window Regulator Brackets (ULSAC # 3028) to the Upper Tube are made of mild steel and assembled with clinch nuts (See Figure 4.2.2.1.5-1).

4.2.2.2 Door Frame Inner Panels Front and Rear Design

The Front Inner Rear and Front Panel were redesigned in the Validation Phase to account for the changes made in the frame structure optimization and in the Mirror Flag Area.

4.2.2.2.1 # 3008 Panel Front Door Inner Front Design

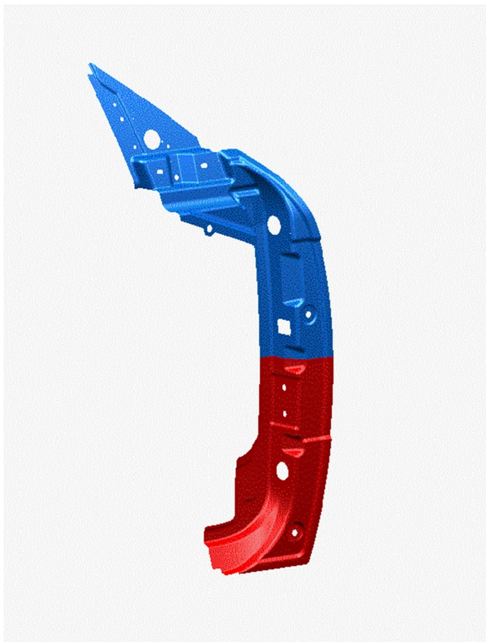


Figure 4.2.2.2.1-1 Panel front door inner front

The Panel Front Door Inner Front (see Figure 4.2.2.2.1-1) was redesigned to replace the one (1) piece Mirror Flag casting with a two (2) piece stamped part design. The design challenge was to integrate as many possible functions previously incorporated into the Concept Phase Mirror Flag design without adding too many additional parts.

The Panel Front Door Inner Front is designed to form the inside of the Mirror Flag and to provide one half of the cavity in which the Outer Beltline Reinforcement is sandwiched together with the Mirror Flag Outer, creating a strong structural node between the Hinge Tube and the Beltline Reinforcement. The part size had to be increased in height and width to incorporate the Mirror Flag and for support of the attachment for the Window Regulator module into the part design with the chosen tailor welded blank design replaces the local 1.2 mm material thickness reinforcement for the Lower Hinge Reinforcement.

The tailor welded blank layout increased the material thickness from 0.6 mm in the concept design to 1.2 mm in the final design with the same mild steel with a yield strength of 140 MPa and was needed to achieve acceptable structural performance. The upper portion of the tailor welded blank is designed with a material thickness of 1.0 mm, also utilizing mild steel with a yield strength of 140 MPa as on the lower portion of the part, and was needed to give the Mirror Flag the strength necessary to support the Outside Rearview Mirror and for the Outer Panel attachment.

4.2.2.2.2 #3020 Assembly Panel Mirror Flag Outer

The Assembly Panel Mirror Flag Outer (See Figure 4.2.2.2.2-1) is designed to form the mounting surface for the Outside Rearview Mirror attachment together with a Front Door Inner Panel Front the two (2) parts form the glass drop channel for the side glass and captures the Outer Belt Reinforcement to build a node which transferred load to and from Hinge Tube.

The Assembly Panel Mirror Flag Outer is assembled with a clinch nut for the Window Regulator module attachment. The part is designed with a material thickness of 1.0 mm in a mild steel material with yield strength of 140 MPa.

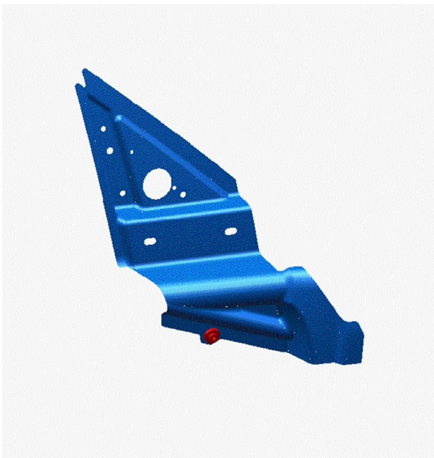


Figure 4.2.2.2.2-1 Assembly panel mirror flag outer

4.2.2.2.3 #3004 Panel Front Door Inner Rear

The Panel Front Door Inner Rear (See Figure 4.2.2.2.3-1) is designed with a 0.6 mm 140 MPa yield strength material. In the optimization process for assembly, the part size was increased to provide more welding surface now overlaid the Latch Tube.

Figure 4.2.2.2.3-1 Panel front door inner rear

This design change resulted form the CAE Analysis for structural performance. The Panel Front Door Inner Rear also provides the attachment locations for the Door Inner Panel module, material thickness of 0.6 mm and 140 MPa mild steel.

4.2.2.3 Door Outer Panel Design

As in the Concept Phase, the design utilizes the ULSAB styling theme for the Door Outer Panel (See Figure 4.2.2.3-1).

Figure 4.2.2.3-1 Door outer panel design

The reason for the tailor welded blank design in the Concept Phase was to enhance the Upper Beltline stiffness of the ULSAC DH door structure and to enhance crash-worthiness. With the redesign of the door structure and the introduction of an ultra high strength steel Beltline Reinforcement, the tailor welded blank design (See Figure 4.2.1.3-1, page 4 of this chapter) could be eliminated and reduced parts cost.

The design feature from the Concept Phase design (similar to the Audi A6 door) where the lower part of the Inner Panel between Inner Front and Rear is stamped onto the Outer Panel and folded to the inside (see Figure 4.2.2.3-2) was maintained in the Validation Phase. This reduces mass by eliminating the hem flange in this area.

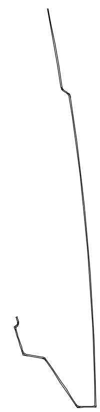


Figure 4.2.2.3-2 Stamped lower part of inner panel

The Door Outer Panel was designed with a material thickness of 0.7 mm utilizing various material grades ranging from BH210, BH260 and DP600. The manufacturing process decided, was stamping.

4.3 Summary

Design of the ULSAC door structure has changed significantly in its transition from the Concept Phase into the Validation Phase. The final ULSAC door structure design is shown in the exploded view (see Figure 4.3-1).

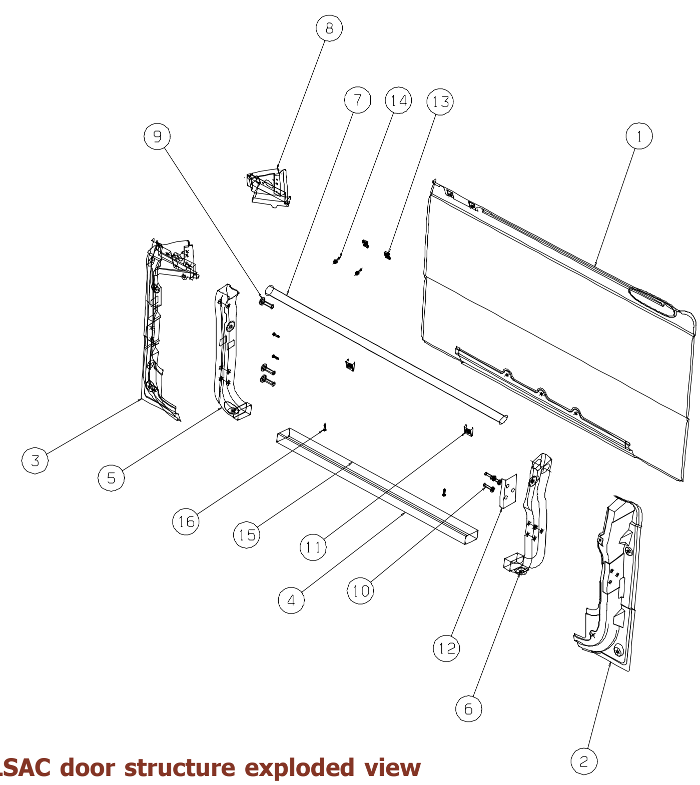


Figure 4.3-1 ULSAC door structure exploded view

The actual part mass and the design material thickness, yield strength, the manufacturing processes utilized for the parts manufacturing are shown in Figure 4.3-2.

Item No.	Part No.	Part Name	Mass (kg)	Material Thickness (mm)	Minimum Yield Strength (Mpa)	Manufacturing Process
1	3000	Panel Front Door Outer RH	4.600	0.7	210	Stamping
2	3004	Panel Front Door Inner Rear RH	0.467	0.6	140	Stamping
3	3008	Panel Front Door Inner Front RH (TWB)	1.130	1.0/1.2	140/140	Stamping
4	3010	Front Door Lower Tube	1.438	1.5	650	Stock Material
5	3012	Front Door Hinge Tube RH	0.653	1.2	280	Tube Hydroforming
6	3014	Front Door Latch Tube RH	0.601	1.0	280	Tube Hydroforming
7	3016	Front Door Outer Belt Reinforcement	0.778	1.0	650	Stock Material
8	3020	Assembly Panel Mirror Flag Outer RH	0.371	1.0	140	Stamping
9	3024	Front Door Hinge Bushing (3@0.041ea.)	0.132	NA	NA	Milling
10	3026	Fornt Door Latch Bushing (3@0.014ea.)	0.039	NA	NA	Milling
11	3028	Assembly Front Door W-Reg Attach. Upper RH (2@0.007ea.)	0.013	0.9	140	Stamping
12	3030	Reinforcement Latch	0.054	1.2	140	Stamping
13	3300	U-Clip M6x1.00 (2@0.011 ea.)	0.021	NA	NA	NA
14	3301	Hex Flange Head M6x15 (2@0.4 ea.)	0.080	NA	NA	NA
15	3312	Adhesive Bonding - Lower Tube	0.070	NA	NA	NA
16	3316	Weld Stud M6x16 (4@0.005 ea.)	0.020	NA	NA	NA
		Mass Door Structure Total	**10.467**			

Figure 4.3-2 ULSAC door structure parts list

The total mass of the ULSAC door structure, measured at 11.47 kg is 1.76 kg below the ULSAC target mass of 12.23 kg. To further reduce the mass, the use of active sheet hydroforming for the Panel Front Door Outer is under investigation. The possibility to use the material thickness from 0.7 mm to 0.6 mm depends on the feasibility on the active sheet hydroforming process, utilized for the Panel Front Door Outer and on the results of the testing for dent resistance and oil canning.

5 CAE Analysis

CAE Analysis is used to support the design and for performance prediction.

Background

In the ULSAC Validation Phase, CAE Analysis was used during the development of the ULSAC Frameless door for support and guidance of the design, and for predicting the structural performance. Due to the fact that the design in the Validation Phase was significantly changed and optimized compared to the concept design, the CAE Analysis ensured that the ULSAC DH would achieve similar performances as the concept door developed in the ULSAC Concept Phase.

5.1 Scope of Work

The objective of the CAE analysis was to develop the mesh and to perform linear and non-linear analysis.

5.1.1 Linear Analysis

For the linear analysis, NASTRAN was used and the following load cases were considered.

Static Door Stiffness

- Vertical Sag Stiffness
- Upper Lateral Stiffness
- Lower Lateral Stiffness

Dynamic Door Stiffness

- Normal Modes

5.1.1.1 Material Properties

For the Linear Analysis, the material properties used were:

Material Properties	
Young's Modulus	= 2.07 x 10^5 MPa
Material Density	= 7.8 x 10^6 kg/m^3
Poisson's Ratio	= 0.3

Fig. 5.1.1.1-1 Material properties

5.1.1.2 Material Thickness

For most of the door components, the material thickness as specified in the parts design is used in the CAE Analysis. The material thickness values are shown in figure 5.1.1.2-1.

Part No.	Name	Thickness (mm)
3000	Panel Front Door Outer	0.70
3004	Panel Front Door Inner Rear	0.60
3008 (1)	TWB - Panel Front Door Inner Front Upper	1.00
3008 (2)	TWB - Panel Front Door Inner Front Lower	1.20
3010	Front Door Lower Tube	1.50
3012	Front Door Hinge Tube	1.20
3014	Front Door Latch Tube	1.00
3016	Front Door Outer Belt Reinforcement	1.00
3020	Panel Mirror Flag Outer	1.00
3030	Reinforcement Latch	1.20

Fig. 5.1.1.2-1 Material thickness values

5.1.2 Non-linear Analysis

The non-linear analysis using LS-DYNA was performed for the following load cases:

- Quasi-static Side Intrusion
- Longitudinal Door Crush

Material specifications for steel used in the ULSAC Program were provided by the ULSAC Consorti um member steel supplying companies.

5.1.2.1 Material Properties

In addition to the material thickness as used in the linear analysis, for the non-linear analysis, the plastic properties were provided by ULSAC Consortium member companies. The yield strength used in the analysis are shown in Figure 5.1.2.1-1.

Part No.	Name	Yield Strengths (MPa)	
3000	Panel Front Door Outer	247	*
3004	Panel Front Door Inner Rear	140	
3008 (1)	TWB - Panel Front Door Inner Front	140	
3008 (2)	TWB - Panel Front Door Inner Front	140	
3010	Front Door Lower Tube	670	*
3012	Front Door Hinge Tube	365	*
3014	Front Door Latch Tube	279	*
3016	Front Door Outer Belt Reinforcement	766	*
3020	Panel Mirror Flag Outer	140	
3030	Reinforcement Latch	140	

*** Steel mill test data**

Figure 5.1.2.1-1 CAE model yield strength input data

For Part No. 3010 Front Door Lower Tube and Part No. 3016 Front Door Outer Belt Reinforcement, the most sensitive parts of the door structure in respect to the analysis results, the tensile strength, and the percentage elongation to failure were provided by the material supplying ULSAC Consortium member company and included in the LS-DYNA input file (see Figure 5.1.2.1-2).

Parameter	Part No. 3010 Front Door Lower Tube	Part No. 3016 Front Door Outer Belt Reinforcement
Tensile Strength	858 MPa	968 MPa
Elongation (A5)	21.50%	17.50%

Fig. 5.1.2.1-2 Input parameters

5.2 CAE Analysis - Model Development

The Finite Element Model was developed with the modeling software HyperMesh and used in both linear and non-linear analysis.

5.2.1 CAE Model - Geometry

Figure 5.2.1-1 shows the full RH door structure model viewed from the inside of the vehicle.

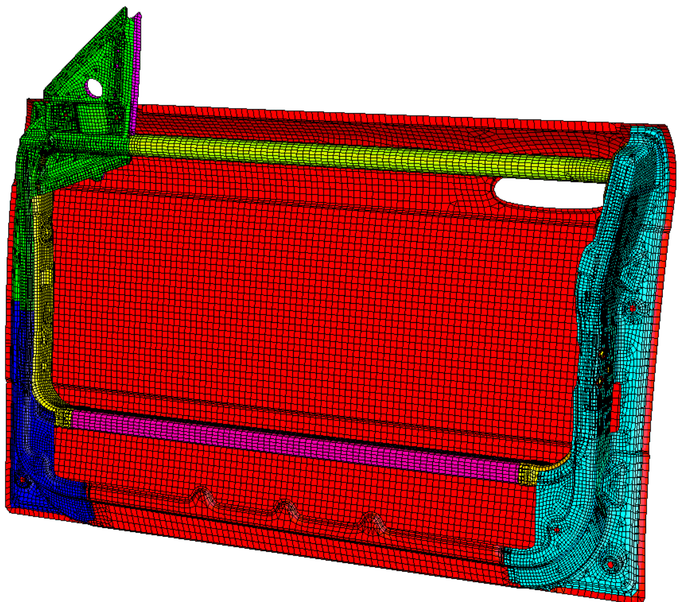


Fig. 5.2.1-1 Door model inside view

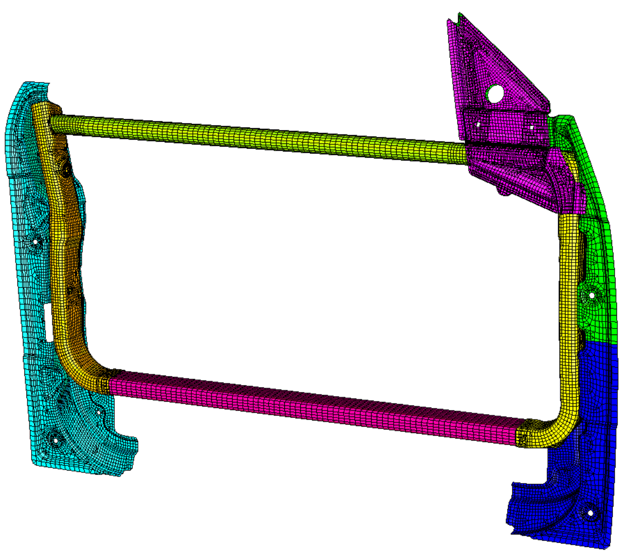


Figure 5.2.1-2 shows the RH door structure model with the outer panel removed, viewed from the outside of the vehicle.

Fig. 5.2.1-2 Door model outside view

5.2.2 CAE Model - Statistics

The number of nodes and elements used in the model are given in table 5.2.2-1 with the number of triangles comprising at 12% of the total number of elements, which is in an acceptable range without over-stiffening the model. In the linear analysis, the bushings used at the hinges and latch locations are modeled as CBAR (linear beam) elements. In the non-linear analysis, the bushings used at latch and hinge locations are modeled as *CONSTRAINED_NODAL_RIGID_BODY elements.

Feature	Number
CQUAD4 Quadrilateral shell element	33,324
CTRIA3 Triangular shell element	4,578
GRID node	36,524

Fig. 5.2.2-1 CAE model statistics

5.2.3 CAE Model - Joining of Components

Spot-welds and laser welds were modeled using RBE2 elements (NASTRAN) and *CONSTRAINED_NODAL_RIGID_BODY elements (LS-DYNA). Spot-weld locations and laser weld locations and lengths were adjusted to represent changes made in the final manufacturing optimization process. The adhesive material between the Panel Front Door Outer and the Lower Tube was not modeled. This has a minimum effect on the structural performance result.

The hem flange was modeled as a single element to represent the three thicknesses (outer panel, inner panel, and folded outer panel). This approach tends to overstrain the hem, but only by a small amount. An analytical study performed on the full door structure model assessed the importance of the hem thickness. When the hem thickness was reduced to 0.1 mm, the static stiffness reduced by a maximum of 1.9%. The over-restrained caused by the single element is therefore considered not critical.

Vertical sag stiffness is sensitive to local conditions.

5.2.4 CAE Model - Hinge & Latch Representation

The door design did not include hinges or a latch. These components were not represented in the model. In the model, the hinges were assumed to be rigid and RBE2 spiders were used at the upper and lower hinge, as well as for the latch location (see Figure 5.2.4-1).

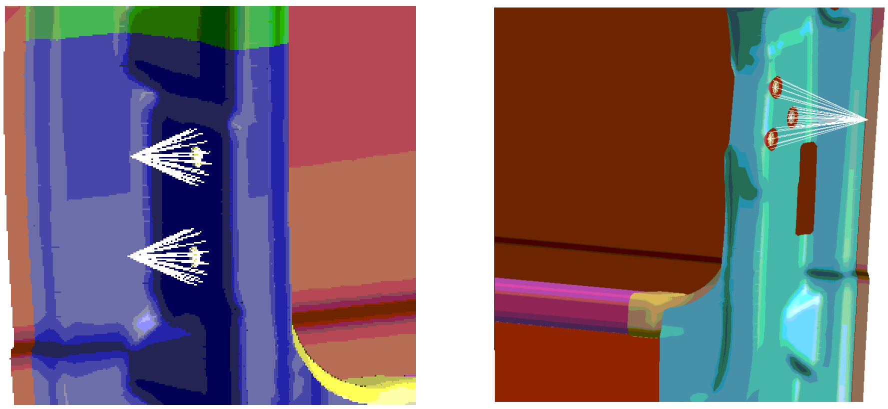


Fig. 5.2.4-1 Spiders at latch and hinge

5.3 CAE Analysis Results

5.3.1 Vertical Sag Stiffness

The boundary conditions for the vertical sag stiffness loadcase are shown in Figure 5.3.1-1. The hinges are fully restrained and the vertical load is applied at the latch.

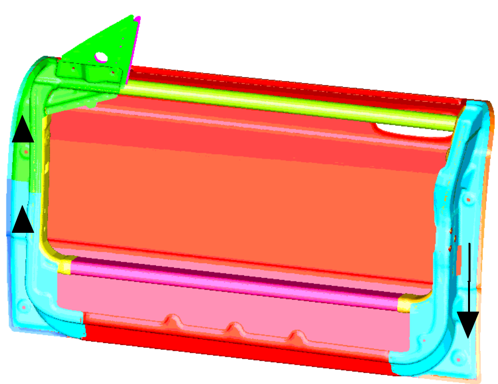


Fig. 5.3.1-1 Boundary conditions for vertical sag analysis

5.3.1.1 Initial Analysis Results

The initial analysis predicted the door sag stiffness at 300 N/mm. This result was based on several assumptions and reflected in the CAE model.

- Design material thickness
- Joining to design specification
- Rigid representation of the bushings at the hinge locations

5.3.1.2 Correlation of Analysis with Test Results

For the correlation of the CAE results with the test results, several adjustments were made to the CAE model to represent the actual ULSAC DH door structure.

- Material thickness was reduced from measurements taken from actual parts
- Reduced laserwelding length
- Replacement of laserwelding with spot welding in Mirror Flag area.
- Non rigid of representatin of bushings at the latch locations

For the two hydroformed components (Part No. 3012 & 3014) the analysis model was updated with the average thickness values for each of the tubular parts with a uniform thickness as soon as they were available. These calculated average values were based on a series of thickness measurements taken from the actual prototype parts (72 measurement spots from the Latch Tube / 48 measurement spots from the Hinge Tube(see Chapter 8 Parts Manufacturing). The approach to use real part thickness values was used to predict the door sag values where the material thickness of all parts and especially the hydroformed parts is very sensitive to the results.

For the ULSAC DH structure build, the laserwelding was reduced as a result of accessability of the laserwelding head at the design specified weld locations. The original design considered the remote laserwelding technology for joining of the stamped Panel Front Inner Rear and Panel Front Inner Front to the front door Hinge and Latch Tube. The remote laserwelding equipment was not available, as planned, at the time of the DH build. This caused the changes from laser to spot welding in the Mirror Flag area and a reduction of laserweld seam lengths. As a result of this CAE model adjustments, the CAE results show the vertical door sag stiffness at 169N/mm, which now correlates in an acceptable 8% range with the test results of 156N/mm.

The strain energy density of the door structure for the vertical door sag loadcase is show in Figure 5.3.1.2-1. The displacements have been magnified to better demonstrate the mode of deformation. (See Appendix for animation).

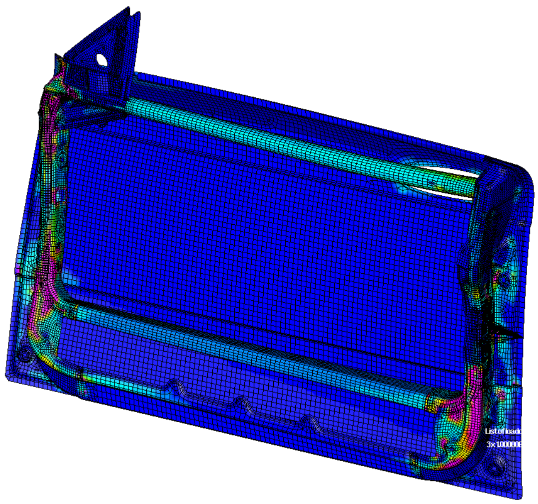


Fig. 5.3.1.2-1 Vertical sag strain energy density

5.4 Upper and Lower Lateral Stiffness

5.4.1 CAE Model Description

The boundary conditions for the upper and lower lateral stiffness are shown in Figure 5.4.1-1 and Figure 5.4.1-2.

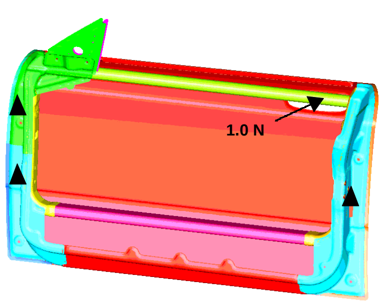


Fig. 5.4.1-1 Boundary conditions upper lateral stiffness analysis

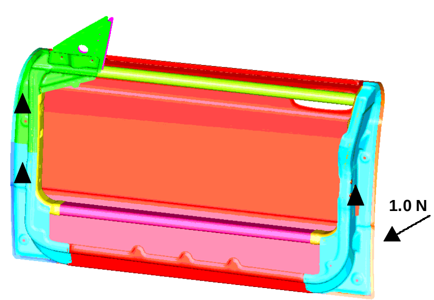


Fig. 5.4.1-2 Boundary conditions lower lateral stiffness analysis

Upper and lower lateral stiffness targets were carried over from the ULSAC Concept Phase.

In both cases, the hinges are fully restrained and the latch is restrained except for roll rotation. For the upper loadcase, the horizontal load is applied to the inboard side of the upper door beam. For the lower loadcase, the load is applied to the outer panel at the height of the lower door beam.

5.4.2 Analysis Results

The ULSAC targets for upper and lower lateral stiffness were originally presented in the ULSAC Concept Phase as a linear stiffness of 94 N/mm for both loadcases. The use of the linear stiffness can be misleading as the results are dependent on the vertical location of the applied load. (As the distance between the load point and the horizontal plane containing the latch increases, the linear stiffness will increase, but the rotational stiffness will remain unchanged). The linear stiffness targets of 94 N/mm were therefore translated into lateral stiffness of 127 Nm/deg for the upper and 48 Nm/deg for the lower loadcases respectively Figure 5.4.2-1 and Figure 5.4.2-2 visualize the strain energy density for the upper and lower lateral stiffness loadcases.

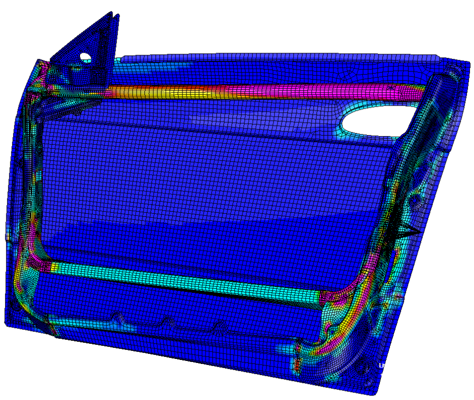


Fig. 5.4.2-1 Upper lateral stiffness strain energy density

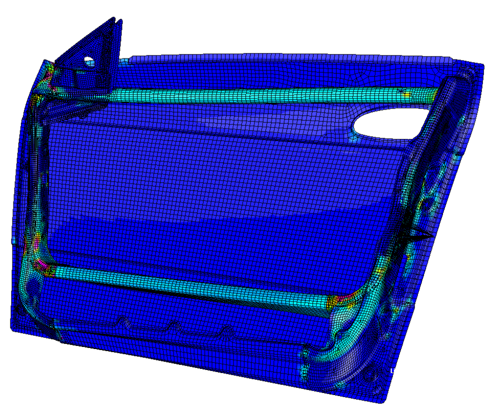


Fig. 5.4.2-2 Lower lateral stiffness strain energy density

The analysis results (see Figure 5.4.2-3) show that the ULSAC Validation door structure design achieves higher values than the targets set in the ULSAC Concept Phase.

Structural Performance	ULSAC Concept Phase Target	ULSAC Validation CAE Analysis Results
Upper Lateral Stiffness Nm/deg	127	**245**
Lower Lateral Stiffness Nm/deg	48	**250**

Fig. 5.4.2-3 CAE analysis lateral stiffness results

5.5 Dynamic Stiffness

5.5.1 CAE Model Description

To analyze the dynamic stiffness of the ULSAC Validation door structure, a NASTRAN modal analysis was performed. In a standard physical stiffness test, a door is suspended with rubber strings to ensure a minimum of restraint. For the CAE Analysis all boundary conditions were removed from the analysis model.

5.5.2 Analysis Results

The results of the dynamic stiffness analysis are shown in Figure 5.5.2-1, with the first mode (outer panel mode) at 41.8 Hz, just above our target of 40 Hz. No physical testing was performed. (See Appendix for animations for modes# 1, 2, 3).

Mode #	Frequency	Description
-	< 0.02 Hz	6 Rigid body modes
1	41.8 Hz	Outer panel mode
2	45.1 Hz	Outer panel mode
3	52.4 Hz	Global Torsion

Fig. 5.5.2-1 CAE analysis - dynamic stiffness results

Analysis results show 41.8 Hz for the first mode.

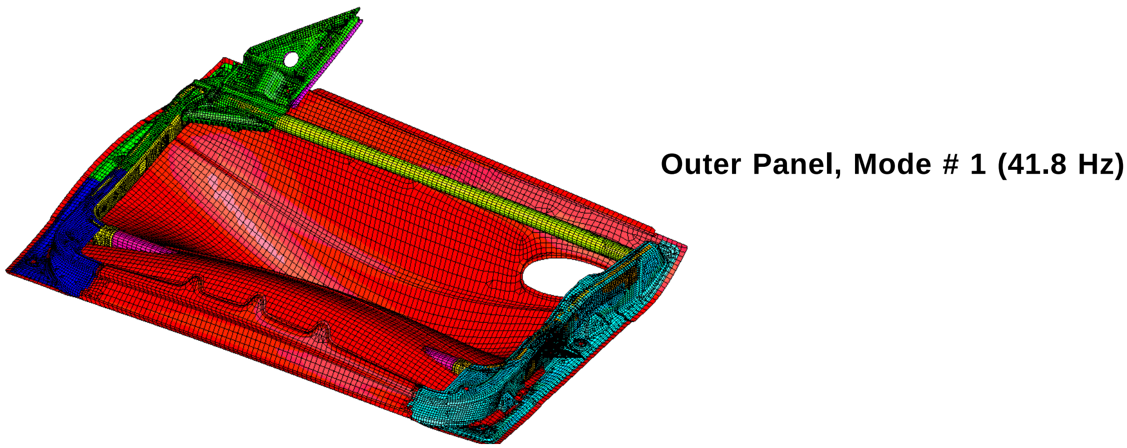


Fig. 5.5.2-2 Dynamic stiffness results

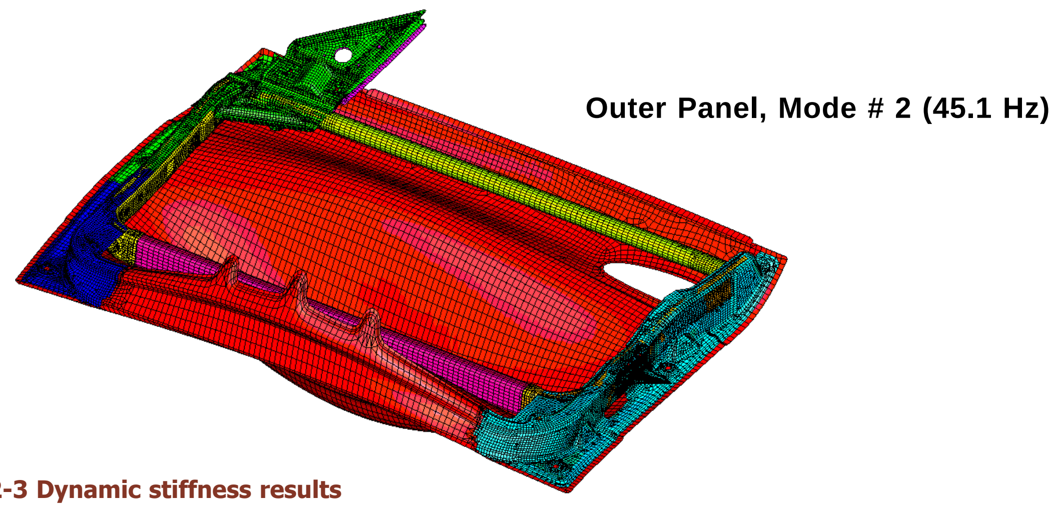


Fig. 5.5.2-3 Dynamic stiffness results

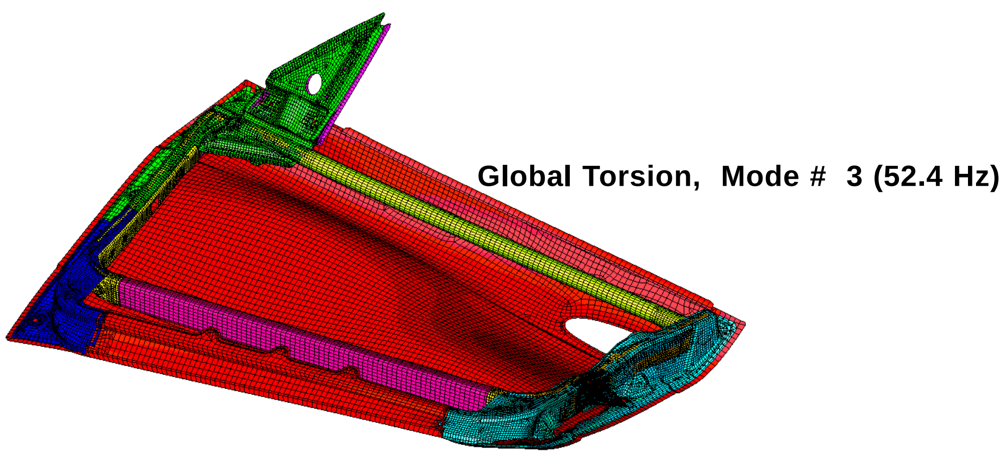


Fig. 5.5.2-4 Dynamic stiffness results

Quasi-static side intrusion analysis is used to predict safety of the ULSAC door structure design.

5.6 Quasi-Static Side Intrusion

One of the requirements of the U.S. Federal Safety Standard FMVSS 214 is a quasi-static door test. In this test a rigid impactor loads the center of the door which is mounted in the vehicle. The performance criteria are given in Figure 5.6-1. The ULSAC door structure was not designed to fit into a specific vehicle, and can not be analyzed in accordance with FMVSS 214. To analyze the quasi-static side intrusion performance of the ULSAC door structure, a similar analysis to FMVSS 214 was performed. The results are not comparable to FMVSS 214 Standard, because the CAE model does not account for the body structure surrounding the door, which exists in a real vehicle such as B-pillar, Hinge-pillar and Rocker, and therefore does not take into account the deformation of these parts appearing in a standard FMVSS 214 test. In the ULSAC quasi-static side intrusion analysis, the goal was to get as close as possible to the FMVSS 214 requirements and to compare the results with the test results of the benchmarked frameless door structures, tested under the same conditions as the ULSAC door structure in the CAE Analysis, and to achieve similar performance.

FMVSS 214 Criterion	Description	FMVSS Limit
Initial Crush Resistance	Average force required to deform the door over the initial 6 inches (152.4mm) of crush	at least 10.01kN (2250lbf)
Intermediate Crush Resistance	Average force required to deform the door over the initial 12 inches (304.8mm) of crush	at least 15.57kN (3500lbf)
Peak Crush Resistance	Largest force recorded over the entire 18 inch (457.2mm) crush distance	at least 31.14kN (7000lbf) or twice the curb-weight of the vehicle, whichever is less

Fig. 5.6-1 FMVSS 214 Requirements

5.6.1 CAE Model Description

The finite element model is shown in Figure 5.6.1-1. The door panel has been removed from the image. The hinge and latch areas are attached to rigid fixtures restrained in all directions except rotation around the vertical (Z axis). The location of the hinges is shown in Figure 5.6.1-2. The rigid impactor is sized and positioned in accordance with FMVSS 214. A velocity boundary condition was used to move the impactor towards the door. The velocity of the impactor was chosen to minimize dynamic (inertia) effects.

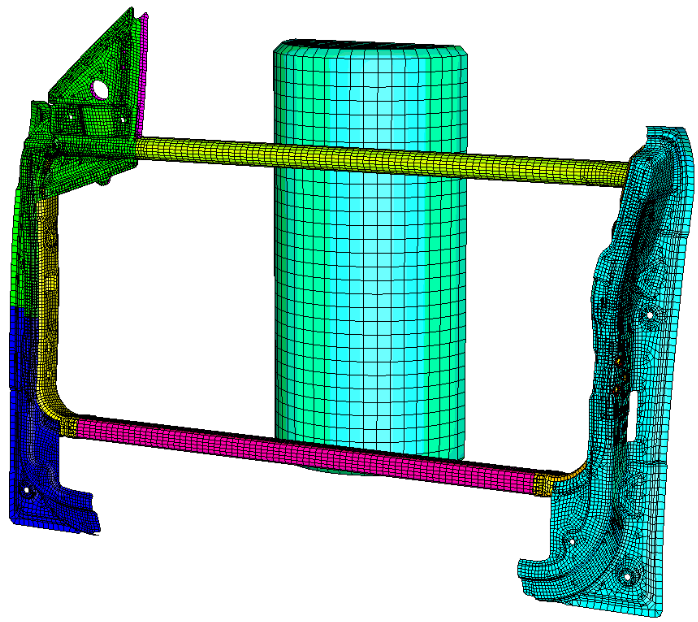


Fig. 5.6.1-1 CAE model side intrusion

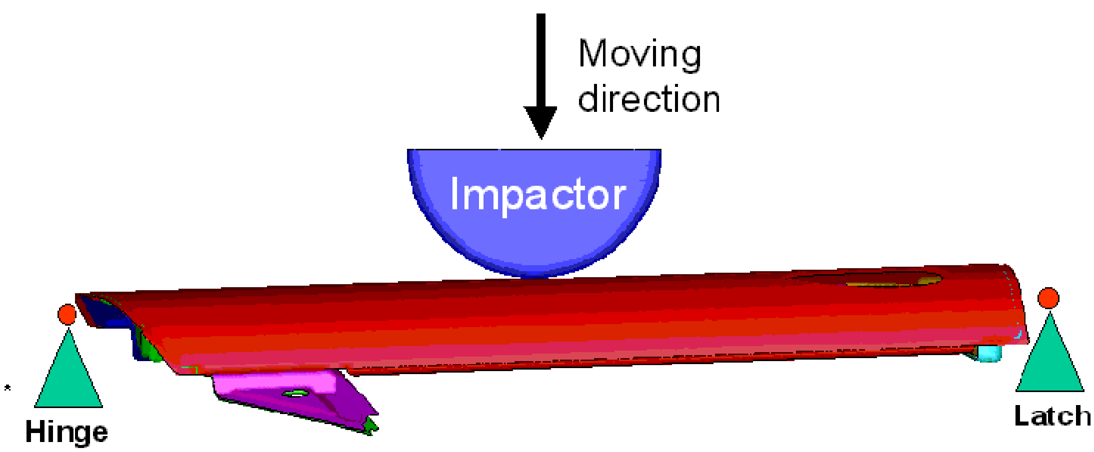


Fig. 5.6.1-2 Location of fixture hinges

5.6.2 Analysis Results

The side intrusion analysis was performed using LS-DYNA. The deformation of the door at 6" and 12" in shown if Figure 5.6.2-1 and Figure 5.6.2-2 respectively. The distribution of effective plastic strain at 6" and 12" is shown in Figure 5.6.2-3 and Figure 5.6.2-4 respectively. Figure 5.6.2-5 shows the force/displacement characteristic of the door structure.

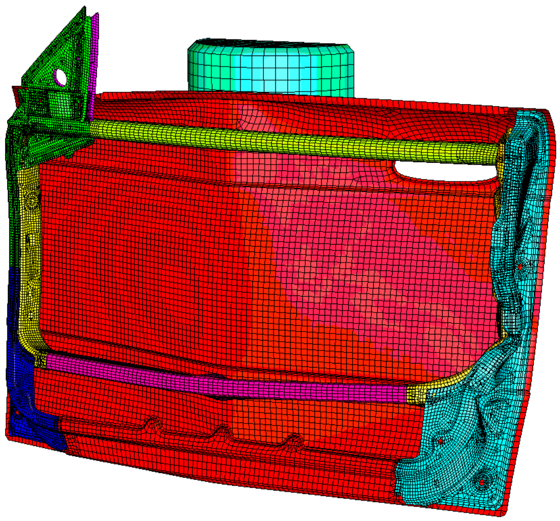


Fig. 5.6.2-1 Deformation at 6 inches(152.4 mm)

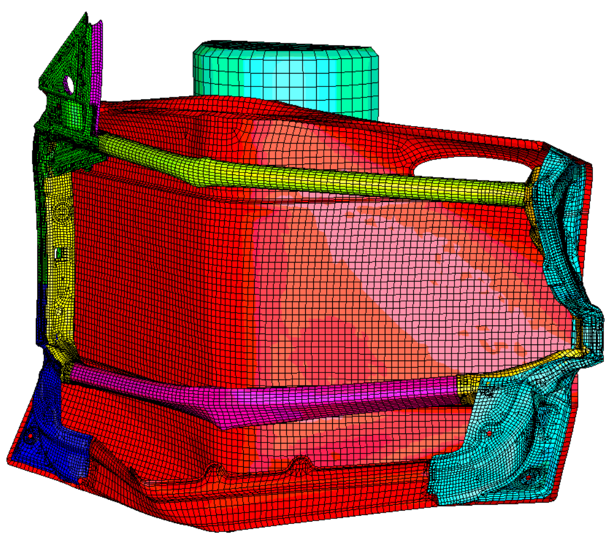


Fig. 5.6.2-2 Deformation at 12 inches (304.8

The ULSAC door structure shows good intrusion performance.

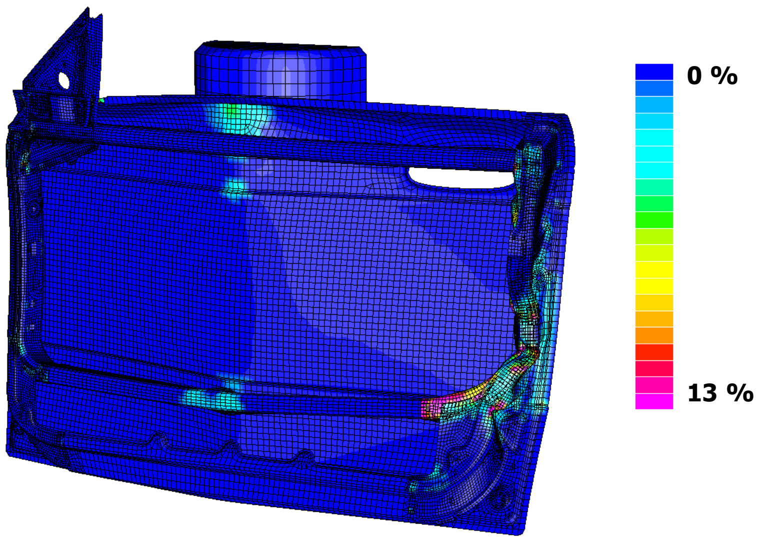


Fig. 5.6.2-3 Plastic strain at 6 inches (152.4 mm)

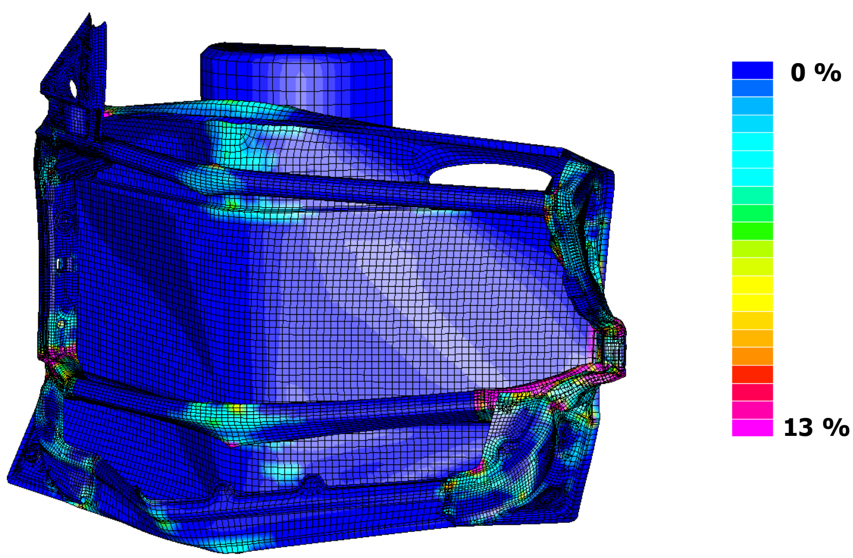


Fig. 5.6.2-4 Plastic strain at 12 inches (304.8 mm)

Analysis shows results that are close to FMVSS 214 requirements.

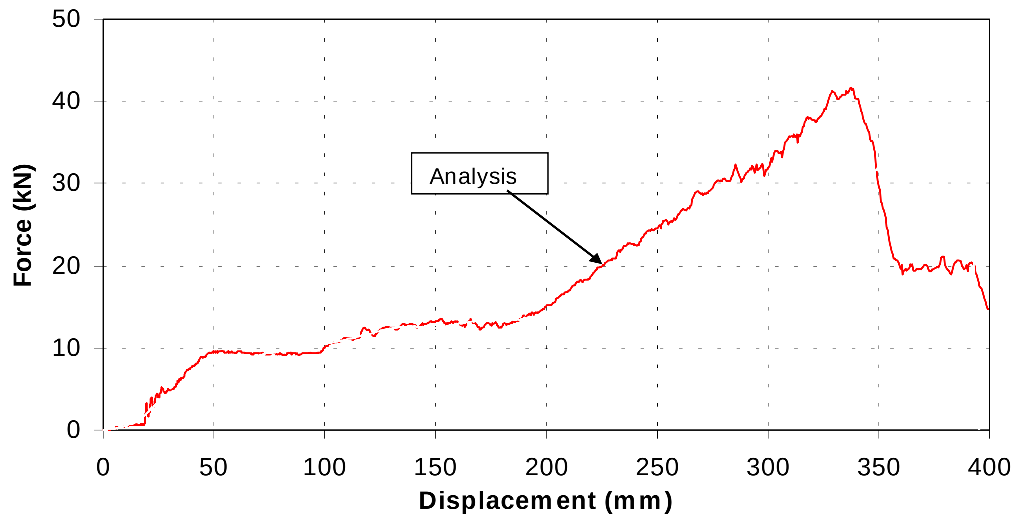


Fig. 5.6.2-5 Force/displacement characteristics

The ULSAC door structure shows good intrusion performance in the analysis with levels close to the FMVSS 214 requirements, especially for the initial crush resistance, which is normally the most difficult target to achieve (see Figure 5.6.2-6).

Criterion	FMVSS 214 Requirements	ULSAC CAE Analysis Results
Initial Crush Resistance (average force at 6 inches of intrusion)	≥ 10.1 kN	8.53 kN
Intermediate Crush Resistance (average force at 12 inches of intrusion)	≥ 15.57 kN	14.92 kN
Peak Crush Resistance	31.14 kN	41.66 kN

Fig. 5.6.2-6 Quasi-static side intrusion analysis summary

5.7 Longitudinal Door Crush

In a front or offset vehicle impact, the strength of the door can be an important contributing factor in the overall vehicle performance for crashworthiness. Since no vehicle data is available, the ULSAC door structure was analyzed in isolation. No physical testing was performed, and no objective performance criteria is available against which to assess the performance of the ULSAC design.

Longitudinal crush analysis to assess door strength.

5.7.1 CAE Model Description

In a front impact the door is loaded by the vehicle body's latch and hinge pillars. Therefore, these needed to be included in the CAE model (see Figure 5.7.1-1). As no geometry was available, these loading surfaces are modeled by offsetting the hinge and latch surfaces of the door. Figure 5.7.1-2 shows the horizontal section cut through the rear of the door near the latch. The door elements are shown in black, the elements representing the latch pillar are shown in red. The same modeling technique was used for the hinge pillar. A rigid hinge pillar represenation was accelerated at 20g rearward into the door structure to crush the door. The crush force, up to a deplacement of 200 mm, was recorded. This acceleration is typical of the vehicle acceleration seen in a full vehicle offset deformable barrier test.

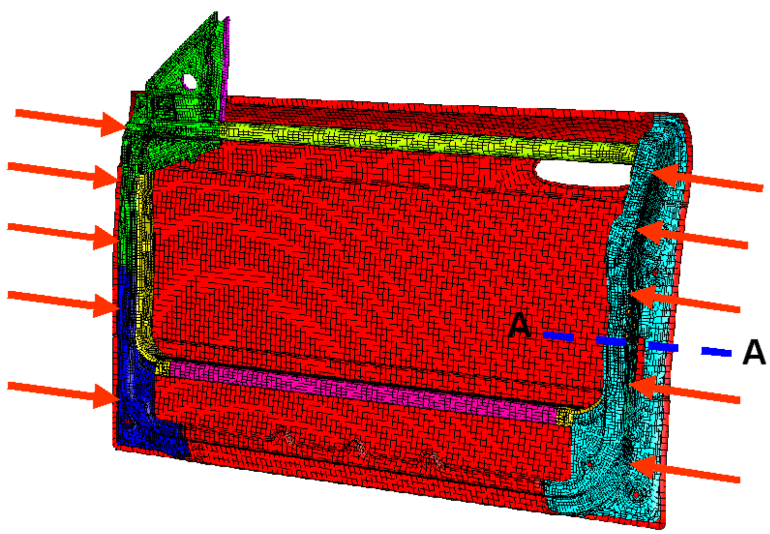


Fig. 5.7.1-1 CAE model set up

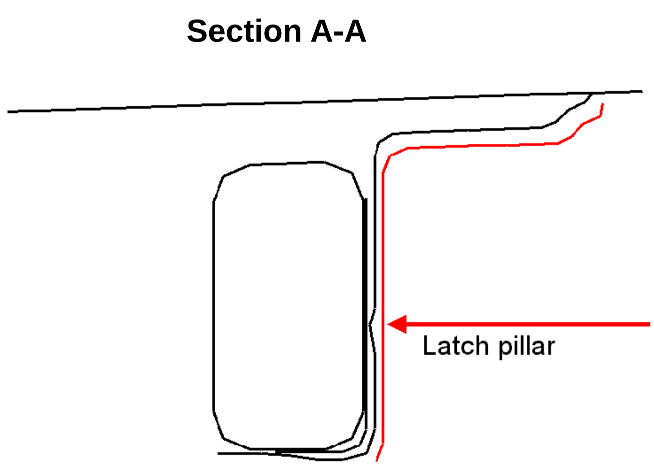


Fig. 5.7.1-2 CAE model - Section AA

5.7.2 Analysis Results

The mode of deformation for 90mm longitudinal crush and 200mm longitudinal crush of the door structure is shown in Figure 5.7.2-1 and 5.7.2-2, respectively. The vehicle latch pillar is fully restrained (right side of image). The vehicle hinge pillar impacts the door structure (moving from the left to the right side of the image). The distribution of effective plastic strain for 90mm longitudinal crush and 200mm of longitudinal crush are shown in Figure 5.7.2-3 and Figure 5.7.2-4, respectively, with the contour bands spanning from 0 to 13%. The analysis shows significant deformation in the upper beam and the door outer panel at 200mm crush with the lower beam not buckled.

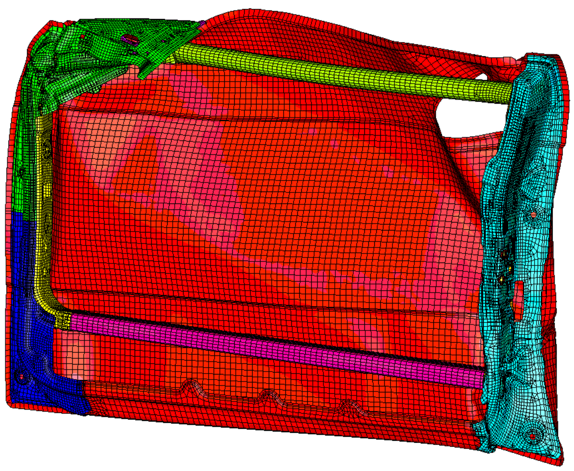


Fig. 5.7.2-1 Deformation at 90mm

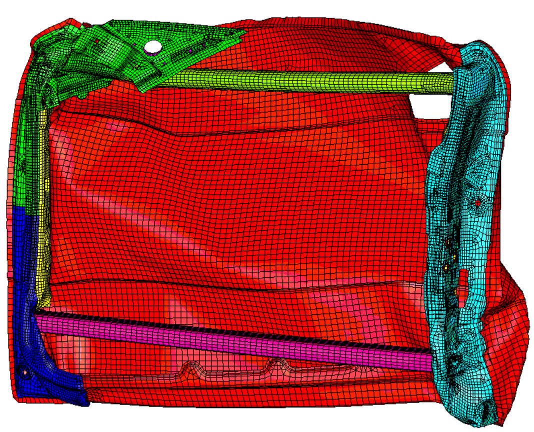


Fig. 5.7.2-2 Deformation at 200mm

The lower beam is not buckled at 200mm crush.

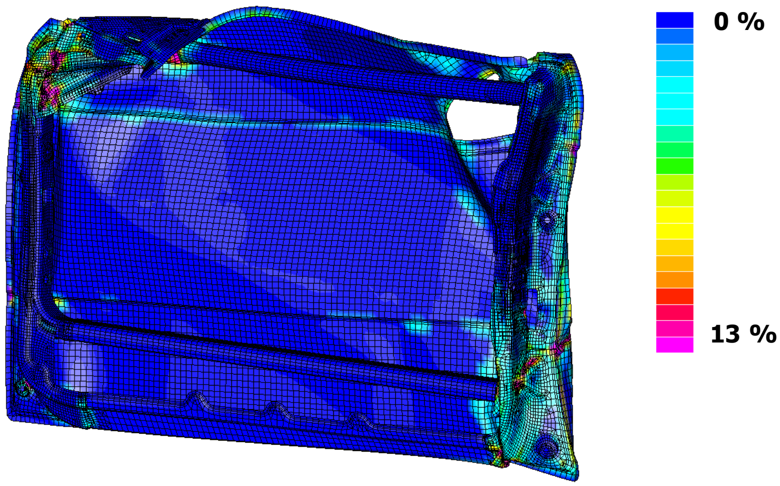


Fig. 5.7.2-3 Plastic strain at 90mm

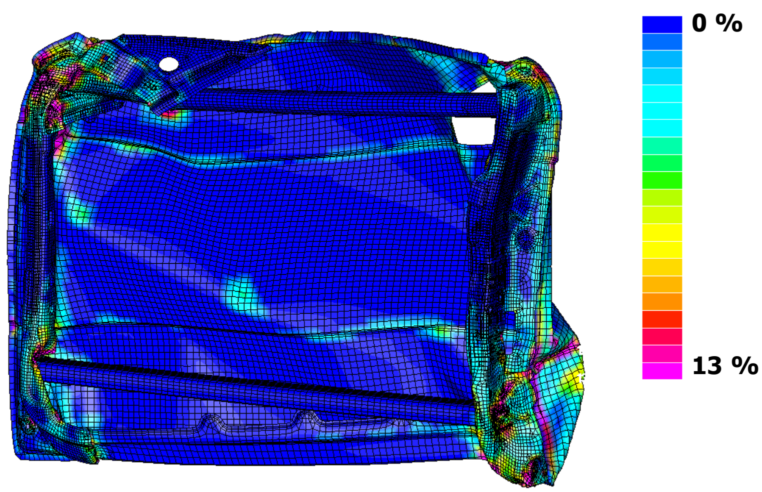


Fig. 5.7.2-4 Plastic strain at 200mm

The ULSAC door structure would make considerable contribution to vehicle crash load management in front impact events.

The force/crush characteristics of the door structure are shown in Figure 5.7.2-5. The graph shows the total force required to crush the door and also the forces carried by the outer panel, the lower beam and the upper beam. A total peak crush force of 60 kN and a sustained crush force of 20 kN are both sufficiently high to suggest that this door structure would make a considerable contribution to crash load management of a full vehicle in a front impact event.

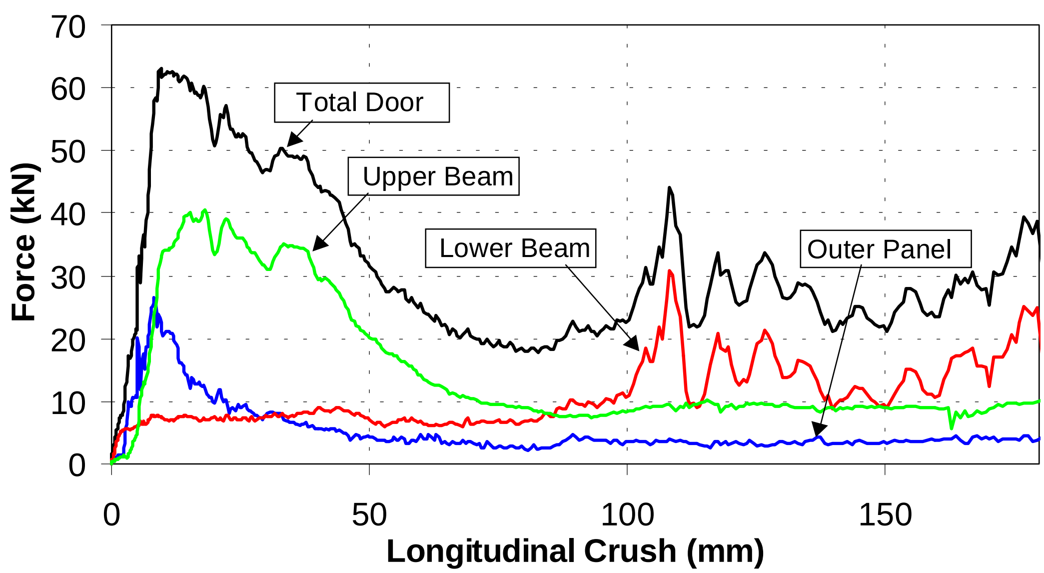


Fig. 5.7.2-5 Force/crush characteristics

6 Materials & Processes

The philosophy "Production Intent" was used when selecting materials for the ULSAC door.

Background

The rationale behind the material selection varied from part to part. Always having "Production Intent" in mind, the focus was on production-ready materials, not on materials that were only available in the laboratory.

To reach the targets which were set in the Concept Phase, the ULSAC Consortium Material Experts decided to use materials with minimum yield strength of 210 MPa for the Panel Front Door Outer.

Many options were considered to achieve the 210 MPa yield strength level for the door panel outer. This could be done by using micro-alloyed high strength steel, bake-hardening steel, interstitial free (IF) steel, isotropic steel and dual phase steel.

Due to demands for good formability, the Front Door Inner panels were manufactured in mild steel with minimum yield strength of 140 MPa. The Bracket Front Door Remote Mirror was originally designed as a thin wall casting. In the Validation Phase, it was decided to replace the Bracket Front Door Remote Mirror with two (2) stampings, due to insufficient tolerances and the high cost of material for such a part.

During the Concept Phase, calculations for side intrusion and longitudinal crush of the door concepts were made. These calculations showed that using high strength steels could lead to weight savings. In the Validation Phase, the door was made using two (2) high strength steel hydroformed tubes with a minimum yield strength of 280 MPa, one (1) a lower rectangular tube and one (1) outer belt reinforcement tube representing ultra high strength steel material exceeding yield strength of 650 MPa.

6.1 Material Selection

6.1.1 Definition of Strength Levels

In order to use minimum materials, master item materials were defined by thickness and strength levels. The same master item material could be used for different parts as long as thickness and strength levels were met. As long as the part manufacturers and forming experts had no concerns, this approach was used.

Mild Steel, High Strength Steel and Ultra High Strength Steel were used to manufacture the ULSAC door.

The definition of material strength levels used in the ULSAC Program is shown in Figure 6.1.1-1. This definition was chosen in order to harmonize the steel grade definitions for the international ULSAC Consortium, involving steel companies from around the world. This definition supports the goal that the ULSAC door can be built in every region of the world.

Minimum Yield Strength	Definition
$\geq$ 140 MPa	Mild Steel
$\geq$ 210 MPa	High Strength Steel
$>$ 550 MPa	Ultra High Strength Steel

Fig 6.1.1-1 Definition of material strength levels

Mild Steel Definition

Mild steel is a material with a yield strength level of 140 MPa. This material has no fixed minimum yield strength but does have a minimum elongation. Mild steels are the most common steels used in auto making today. This is because mild steel has forming advantages compared to high strength steel.

High Strength Steel Definition

The steel industry has developed various high strength steel qualities. High strength steels are defined in the ULSAC program as steels with yield strength of 210 MPa through 550 MPa on the finished part. These strength levels could be achieved by using, i.e. micro-alloyed steels, phosphor-alloyed steels, bake-hardenable steels, interstitial-free (IF) steels, isotropic steels and dual-phase steels.

Ultra High Strength Steel Definition

Ultra high strength steels are defined as steels with yield strength of more than 550 MPa on the finished part. In the ULSAC these materials were used for parts where an additional strength for an impact (e.g. side impact) was required. The material used in ULSAC for the door side impact protection tubes is dual-phase steel.

6.2 Material Requirements

6.2.1 General Requirements - Sheet

General requirements for the material on ULSAC include thickness tolerances, coating requirements and coating tolerances. The requirements are as follows:

- Thickness of blanks must measure +0.00mm/-0.02mm of the specified thickness for the 0.7mm Panel Front Door Outer, the Mirror Flag and the Panel Front Door Inner parts and +0.00mm/-0.02mm for the 0.6mm Panel Front Door Outer
- Material thickness includes the coating thickness
- Coating may be electro-galvanized (Zn only) or hot dip (Zn or FeZn)
- Coating thickness must be 65 gram/m^2 maximum (0.009mm) per side with coatings on both sides

Material had to be verified to specification by the supplier prior to shipping to part manufacturer.

6.2.2 General Requirements - Tubes

The general requirements for the tubes used in the ULSAC Program are:

Front Door Lower Tube

- Outside dimension of tube must measure 30mm +0.00/-0.5mm x 55mm +0.00/-0.5mm (7.5mm +0.00/-0.5mm radii)
- Wall thickness must measure 1.5mm +0.00/-0.05mm
- Total tube length must measure 1200mm
- Material thickness includes the coating thickness
- Coating may be EG (zinc only) or hot dip (Zn or FeZn)
- Coating thickness must be 65 gram/m^2 maximum (0.009mm) per side with coatings on both sides

Material was secured from in-process orders to be as close as possible to the general guidelines.

Front Door Outer Belt Reinforcement

- Outside dimension of tube must measure 34 mm +0.10/-0.00mm
- Wall thickness must measure 1.0 mm +0.00/-0.02mm
- Total tube length must measure 1300 mm
- Material Thickness includes the coating thickness
- Coating may be EG (zinc only) or hot dip (Zn or FeZn)
- Coating thickness must be 65 gram/m^2 maximum (0.009mm) per side with coatings on both sides

The requirements for the hydroformed Latch/Hinge tubes are specific according to the tube hydroforming process and are mentioned later in the Hydroforming section.

Specifications for the hydroformed tubes are specific according to the tube hydroformed process.

6.2.3 Requirements - Tubes for Hydroforming

Front Door Hinge Tube/Latch Tube:

Quality

Feature:	Precision steel tube according to the following specifications
Material:	Zinc coated on both sides
Yield Strength:	≥ 280 MPa on finished parts
Total Elongation:	≥ 30% (longitudinal and transverse)
Uniform Elongation:	≥ 18%

Dimensions and Tolerances

Outside Diameter:	48 mm +0.10/-0.00mm
Wall Thickness:	Hinge Tube: 1.2mm +0.00/-0.05mm Latch Tube: 1.0mm +0.00/-0.05mm Gage includes coating thickness Coating may be EG (Zinc only) or hot dip (Zn or FeZn) The coating must be 65 gram/m^2 maximum (0.009mm)
Total Tube Length:	1350 mm
Cutting of Tube Ends:	Free of burr No ovalization or cave-in No chamfers Rectangular to longitudinal axis ±0.5°

Appearances of Tube

Surface:	Free of mechanical damage, splatters, etc. No collapsed areas (no indents, bulges, etc.) Free of impurities (swarf, weld chips, etc.)

Welding Requirements

Welding Process:	Laser- or EB-welding or HF-welding
Weld Seam Area:	Outside of tube: Undercut 0.00 mm, no expansion Inside of tube: Undercut <0.15 mm, no expansion No mismatch of edges Free of any porosity Strength similar to base material Sufficient overall roundness of tube

All material for the ULSAC door was normal series production steel representing widely available material.

6.3 Material Supplier Selection

The material supplier selection was done in material group meetings attended by expert representatives of the Consortium member companies, as well as PES' design and manufacturing team. Two material suppliers were selected for each ULSAC part. All of the material was taken from normal series production at the steel mills, and therefore, the ULSAC door structure can be built with widely available material and part manufacturing technology.

Figure 6.3-1 shows the material types and grades in 0.6mm and 0.7mm selected for test door structure build and the material grades selected for the other parts manufacturing according to the design material thickness specification. The blank sizes show the minimimum blank sizes to be delivered to the prototype shops and do not represent production blank sizes.

		Materials Spec.			Blanks
No.	Part Name	Min. Yield Strength (MPa)*	Thick. (mm)	Material Type Selected	Min Blank Size (mm)
3000	Panel Front Door Outer - Stamped RH	210	0.7	BH210	1700 x 1350
		210	0.7	DP500	1700 x 1350
		210	0.7	BH260	1700 x 1350
		210	0.7	IF Rephos 260	1700 x 1350
		210	0.7	Isotropic 260	1700 x 1350
		210	0.7	DP600	1700 x 1350
3000A	Panel Front Door Outer - Stamped RH	210	0.6	BH210	1700 x 1350
		210	0.6	DP500	1700 x 1350
		210	0.6	BH260	1700 x 1350
		210	0.6	IF Rephos 260	1700 x 1350
		210	0.6	Isotropic 260	1700 x 1350
		210	0.6	DP600	1700 x 1350
3004	Panel Front Door Inner Rear RH	140	0.6	Mild	1100 x 600
3008	Panel Front Door Inner Front RH (TWB)	140	1.0 1.2	Mild	900 x 800 600 x 800
3010	Front Door Lower Tube RH	650	1.5	DP800	30x55 rec. x 1200
3012	Front Door Hinge Tube RH (48mm outer diameter)	280	1.2	HSST280	48 dia. x 1000
3014	Front Door Latch Tube RH (48mm outer diameter)	280	1.0	Isotropic 280	48 dia. x 1000
3016	Outer Belt Reinforcement RH (34mm outer diameter)	650	1.0	DP800	34 dia. x 1300
3020	Panel Mirror Flag Outer	140	1.0	Mild	600 x 600
3030	Reinforcement Latch	140	1.2	Mild	200 x 150

* Minimum yield strength as required by design on finished part

Figure 6.3-1 Material Selected for Test Door Structure Build

The Panel Front Door Inner Front features a tailor welded blank with a 1.0/1.2 mm thickness.

6.3.1 Material Documentation

An independent institute tested selected materials used for part manufacturing. Figures 6.3.1-1, 6.3.1-2 and 6.3.1-3 include the mechanical properties, coating applied and the chemical material properties.

Coatings used for the ULSAC door material were hot-dip galvanized (GI), electro-galvanized (EG) or galvannealed (GA). The tube parts do not have r-values because the material was delivered and tested as a tube.

Part No.	Delivered Material Properties	Material Thickness (mm)	Yield Strength (0.2% offset) (MPa)	Tensile Strength (MPa)	Elongation A80 (%)	r-value	n-value	Coating
3000	BH210	0.62	247	358	39	2.10	0.19	GI
3000	BH260	0.61	260	389	31	1.30	0.17	GA
3000	DP600	0.60	343	614	37	0.80	0.22	GI
3000	BH210	0.71	245	348	37	2.00	0.15	GI
3000	BH260	0.70	250	380	34	1.20	0.17	GA
3000	DP600	0.69	341	616	28	0.90	0.21	GI
3004	Mild	0.60	150	294	43	1.98	0.23	GI
3008-1	Mild	1.02	174	308	48	2.40	0.21	GA
3008-2	Mild	1.23	177	301	50	2.40	0.20	GA
3010	DP800	1.56	650	868	13	N/A	0.04	EG
3012	HSS280	1.20	357	394	37	N/A	0.08	GI
3014	Isotr.280	0.97	273	361	41	NA	0.19	EG
3016	DP800	0.96	848	999	11	N/A	0.05	GI
3020	Mild	1.02	154	291	52	1.72	0.23	GI
3030	Mild	1.23	177	301	50	2.40	0.20	GA

Figure 6.3.1-1 Mechanical material properties as tested

For the try-out, all six (6) materials in 0.6 mm and 0.7 mm, were available for the Panel Front Door Outer stamping (see Fig. 6.3-1). The Panel Front Door Outer was stamped in all material grades. The ULSAC Consortium made the final decision for the three (3) materials for the Panel Front Door Outer, to be used for the ULSAC DH build as listed in Figure 6.3.1-1.

Material properties and material chemical properties were documented before being shipped to part manufacturer.

			Chemical Composition (%)							
Part No.	Material	Thickness (mm)	C	Mn	P	S	Si	Cu	Sn	Ni
3000	BH210	0.62	0.005	0.411	0.069	0.006	0.011	0.010	0.003	0.020
3000	BH260	0.61	0.065	0.189	0.012	0.005	0.053	0.018	0.013	0.016
3000	DP600	0.60	0.102	1.574	0.013	0.003	0.087	0.025	0.013	0.02
3000	BH210	0.71	0.005	0.25	0.064	0.012	0.008	0.012	0.003	0.021
3000	BH260	0.70	0.065	0.188	0.01	0.009	0.047	0.018	0.011	0.019
3000	DP600	0.69	0.098	1.59	0.012	0.003	0.087	0.025	0.013	0.02
3004	Mild	0.60	0.005	0.144	0.004	0.006	0.013	0.029	0.003	0.01
3008-1	Mild	1.02	0.004	0.164	0.009	0.008	0.011	0.018	0.007	0.014
3008-2	Mild	1.23	0.005	0.171	0.006	0.009	0.021	0.045	0.009	0.019
3010	DP800	1.56	0.129	1.495	0.015	0.005	0.206	0.009	0.002	0.038
3012	HSS280	1.20	0.007	0.521	0.073	0.006	0.082	0.009	0.002	0.019
3014	Isotr.280	0.97	0.040	0.195	0.01	0.007	0.013	0.018	0.004	0.034
3016	DP800	0.96	0.180	1.721	0.013	0.01	0.175	0.017	0.002	0.032
3020	Mild	1.02	0.005	0.116	0.004	0.007	0.015	0.012	0.007	0.005
3030	Mild	1.23	0.005	0.171	0.006	0.009	0.021	0.045	0.009	0.019

Fig 6.3.1-2 Chemical material properties as tested part 1

			Chemical Composition (%)							
Part No.	Material	Thickness (mm)	Cr	Mo	Al	V	Nb	Zr	Ti	Co
3000	BH210	0.62	0.022	0.004	0.055	0.002	0.023	0.001	0.020	0.007
3000	BH260	0.61	0.033	0.004	0.044	0.002	0.005	0.001	0.016	0.004
3000	DP600	0.60	0.426	NA	> 0.5*	0.009	0.010	0.004	0.005	0.006
3000	BH210	0.71	0.019	0.004	0.052	0.001	0.005	0.001	0.003	0.006
3000	BH260	0.70	0.031	0.004	0.039	0.001	0.004	NA	0.016	0.004
3000	DP600	0.69	0.432	NA	> 0.5*	0.009	0.010	0.005	0.005	0.006
3004	Mild	0.60	0.020	0.005	0.079	0.001	0.033	0.001	0.022	0.003
3008-1	Mild	1.02	0.027	0.008	0.041	0.004	0.004	NA	0.074	0.003
3008-2	Mild	1.23	0.026	0.007	0.114	0.004	0.005	0.001	0.078	0.003
3010	DP800	1.56	0.038	0.009	0.053	0.035	0.016	0.001	0.003	0.014
3012	HSS260	1.20	0.019	0.004	0.040	0.003	0.005	NA	0.064	0.004
3014	Isotr.280	0.97	0.021	0.005	0.052	0.002	0.003	NA	0.027	0.007
3016	DP800	0.96	0.424	0.153	0.035	0.01	0.006	0.001	0.004	0.013
3020	Mild	1.02	0.011	0.005	0.041	0.002	0.011	NA	0.057	0.002
3030	Mild	1.23	0.026	0.007	0.114	0.004	0.005	0.001	0.078	0.003

* Value exceeds calibration curve and must be interpreted semiquantitatively.

Fig 6.3.1-3 Chemical material properties as tested part 2

The Panel Front Door Inner Front features a tailor welded blank with a 1.0/1.2 mm thickness.

6.4 Tailor Welded Blank

Tailor welded blanks consist of two or more pieces of sheet steel with different material thickness', grades and/or coatings, joined by laser or mash seam welding.

Tailored blanking enables the design engineer to accurately situate the steel within the part precisely where its attributes are most needed. This leads to mass reduction because it allows the design engineer to remove mass that does not contribute to performance.

Tailor welded blanks are currently used in the automotive industry mainly for

- Increased vehicle safety
- Weight Reduction
- Reduction of parts
- Optimization of parts and components
- Cost Reduction

In the ULSAC Program the Panel Front Door Inner Front features a laser-welded tailored blank. The weld line layout is shown in the following figure 6.4-1 and was determined through the results from the CAE Analysis for structural performance.

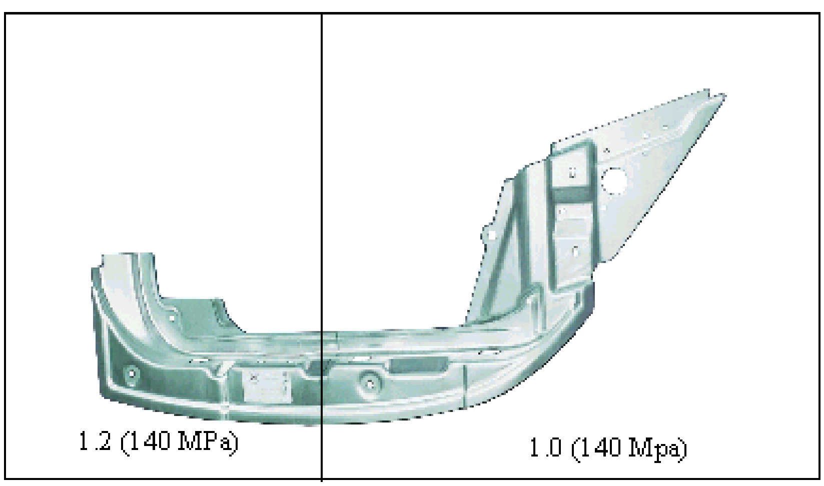


Fig 6.4-1 Panel Front Door Inner Front

Several parts for the ULSAC door, including the Panel Front Door Outer, were manufactured with the stamping process.

6.5 Stamping

Stamping is the most common manufacturing process for making structural parts in the automotive industry. In the ULSAC Program the following parts were manufactured using this process:

- Panel Front Door Outer
- Panel Front Door Inner Front
- Panel Front Door Inner Rear
- Panel Mirror Flag Outer
- Reinforcement Latch

Figure 6.5-1 Stamping Tool

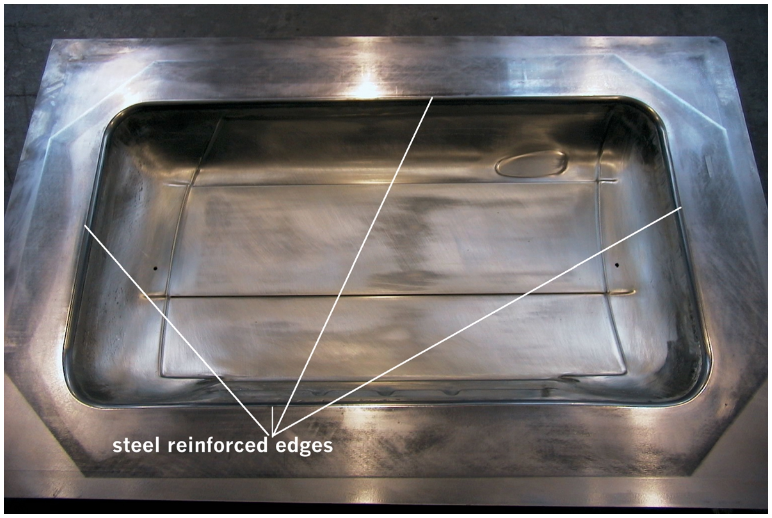


Figure 6.5-2 Stamping Tool

Tubular hydroforming was used in the ULSAC program to improve structural integrity, reduce costs and achieve mass reduction.

6.6 Tubular Hydroforming

6.6.1 General Process Description

Tubular hydroforming is achieving increasing acceptance in the automotive industry for making a wide variety of components. Current applications include suspension frame, body structure, powertrain components and exhaust pipes. The major advantages of tubular hydroforming that have initiated these applications are cost reduction and weight savings, improved dimensional stability, improved structural integrity and increased strength and stiffness of the components.

Depending on the part design, pre-bending and pre-forming operations could be necessary prior to the start of the tubular hydroforming process.

In the tubular hydroforming process, a tube is first placed in the closed cavity of a forming die. Once the ends of the tube are sealed, the tube is filled and pressurized with hydraulic fluid. The internal pressure forces lead the tube to form into the shape of the tool cavity. Most hydroforming processes also use axial force feeding at the tube ends to feed material into the tool during forming. With the application of axial force feeding, higher forming limits at the end of the part can be achieved.

6.6.2 Tube Manufacturing

The ULSAC tubes were manufactured in two different ways: laser-welding and high frequency welding. In the high frequency welding process, a steel strip is continuously roll formed into a tube shape and the longitudinal gap is continously welded by applying high frequency welding process. The welding process is a result of inductive heating and compressing the edges of the steel strip without supplementary material. The following calibration and planing operation (because of the burr) leads to exact tolerances of the tube for the hydroforming process. A high frequency welding machine is shown in figure 6.6.2-1.

Tubes in the ULSAC Program were manufactured with high-frequency welding and laser welding.

Fig 6.6.2-1 High frequency (HF) welding machine

The second process is the use of laser welding for joining. Laser-welding eliminates the burr. This results in the elimination of the planning operation of the burr needed in the high frequency welding process. Compared to the high frequency welding, there is a much smaller heat-effected and dezinced welded zone. The tubes for hydroforming in the ULSAC Program were manufactured both discontinuously and continuously. In the discontinous tube manufacturing process, the tube is formed as a section and then laser welded in a final operation. A discontinuous prototype laserwelding machine by Soudronic of Switzerland is shown in figure 6.6.2-2.

Fig 6.6.2-2 Discontinuous laser welding machine

Several bending operations, as well as the required wall thickness (1.0 mm), made a Latch Tube the more complicated part to manufacture.

6.6.3 Process Steps for Hydroformed Tubes (Latch & Hinge)

Both the ULSAC Latch Tube and the Hinge Tube were manufactured with similar hydroforming process steps. Several additional bending operations and the smaller wall thickness (1.0 mm) made the Latch Tube the more complicated part to manufacture. The process steps for the Latch Tube are described as an example of the tube hydroforming part manufacturing in the ULSAC Program.

6.6.3.1 Latch Tube Manufacturing Process Steps

Due to the three-dimensional curves of the designed part, the straight tube must be pre-bent. The pre-bending was done with a conventional mandrel-bending machine.

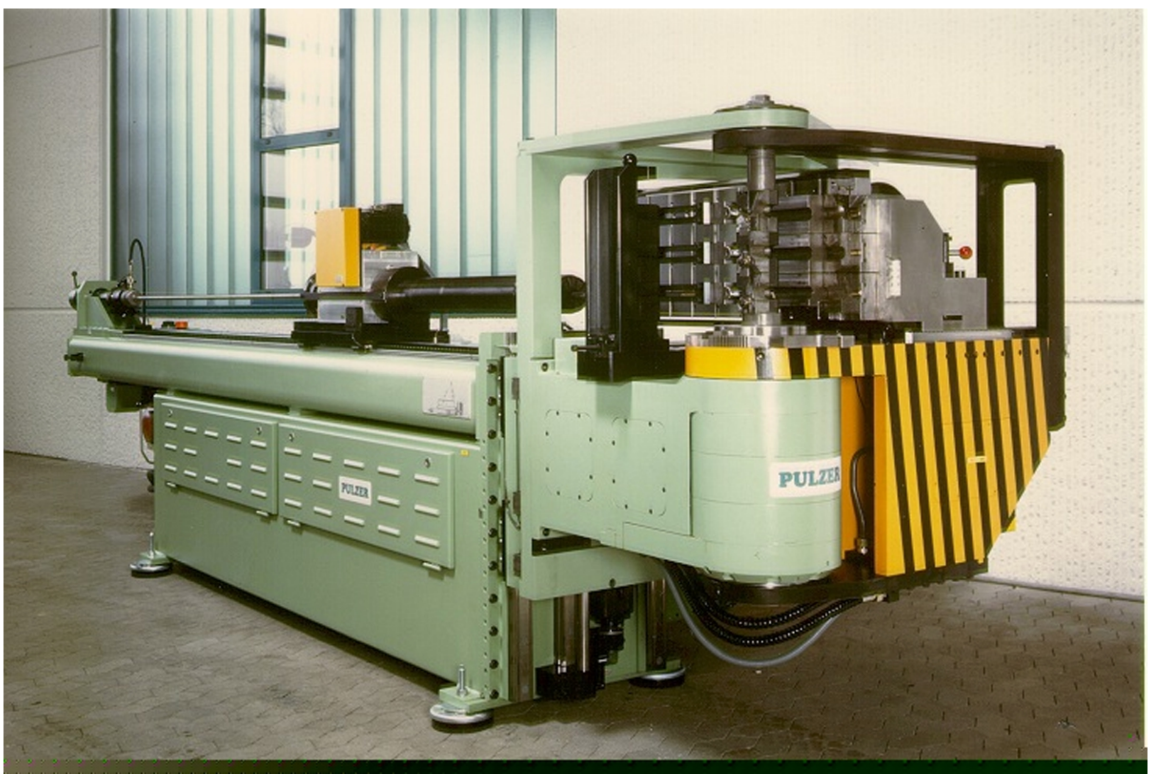


Fig 6.6.3.1-1 Mandrel-bending Machine

Pre-forming must be done in order to achieve a start geometry that fits into the hydroforming tool.

The second step is the pre-forming of the pre-bent tube. This has to be done in order to get a start geometry that fits into the hydroforming tool. The layout of the pre-forming tool is shown in figure 6.6.3.1-2 and 6.6.3.1-3.

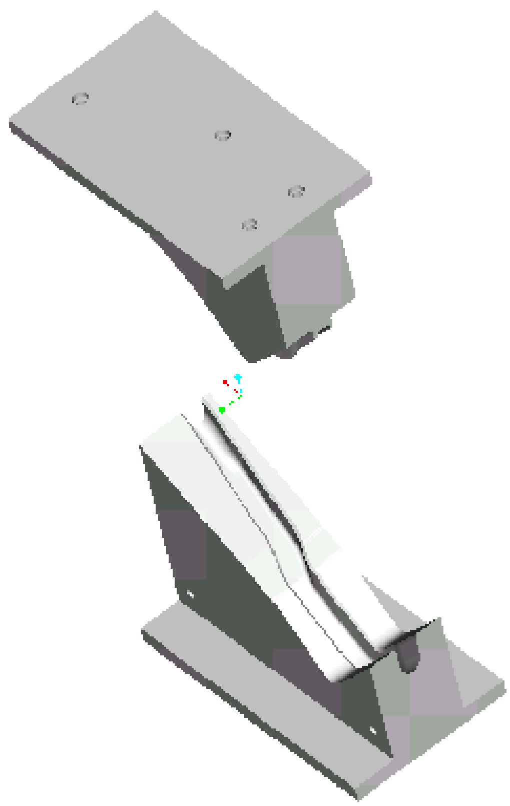


Fig 6.6.3.1-2 Pre-forming tool CAD design

The ULSAC Latch Tube had to be pre-bent, pre-formed and, finally, fully hydroformed in the hydroforming tool.

Fig 6.6.3.1-3 Pre-forming tool

Due to the minimum inner radius, the wall thickness and the yield strength, the pressure had to be raised to 1500 bar.

The final step is the hydroforming process itself. Once the die is finally closed, the internal pressure is increased and the latch tube is calibrated into its final shape.

Due to the minimum inner radius, the wall thickness and the yield strength, the pressure has to be raised to 1500 bar. This required pressure, multiplied by the projected surface, leads to a closing force of about 800 tons. A picture of the hydroforming tool is shown in the figure 6.6.3.1-4.

Fig 6.6.3.1-4 Hydroforming tool

7 Forming Simulations

Stamping and tubular hydroforming simulations were performed to assess critical areas in the forming process.

Background

Predictive tools, like forming simulation, help designers make effective use of new generation high strength steels and new steel-related technologies, as well as common steel grades. Prior to manufacturing, it allows designers to optimize material use and assess forming limits - balancing the demands to reduce cost, weight and complexity.

Stamping and tubular hydroforming simulations were performed to assess feasibility in respect to material thinning, material strain conditions and wrinkling that would exceed forming limit constraints.

There are two different types of forming simulations. In the one-step simulation the material data and the geometry of a designed part is entered into the computer, which then calculates material strains by mapping back to the flat material sheet. This analysis does not simulate the complete forming process, it is performed without any tooling boundary condition input. This part simulation gives designers an indication of what is practically feasible.

The incremental simulation is an entire process simulation where the inputs to the analysis include the part- and the tool geometry, the material properties of the part, the blank size and shape, the system friction, press conditions and the draw-bead effects. The outputs show levels and distribution of material strain, failure prediction, thickness profiles and wrinkling tendency.

7.1 Forming Limit Diagram

7.1.1 Creation of Forming Limit Diagrams

Circle Grids, etched onto sheet-metal parts, are used to determine the deformation capability regarding the distribution, direction and quantity. This analysis results in a Forming Limit Diagram (FLD).

The ellipses that result from the circles during the forming process were measured on major and minor axes. These measured values were converted to percentage or logarithmic deformation values related to the diameter of the starting circle.

Circle Grids, drawn onto sheet metal, are used to determine the deformation which results in a Forming Limit Diagram.

Figure 7.1.1-1 shows a FLD where the major strain ε_1 is applied on the y-axis and the minor strain ε_2 is applied on the x-axis.

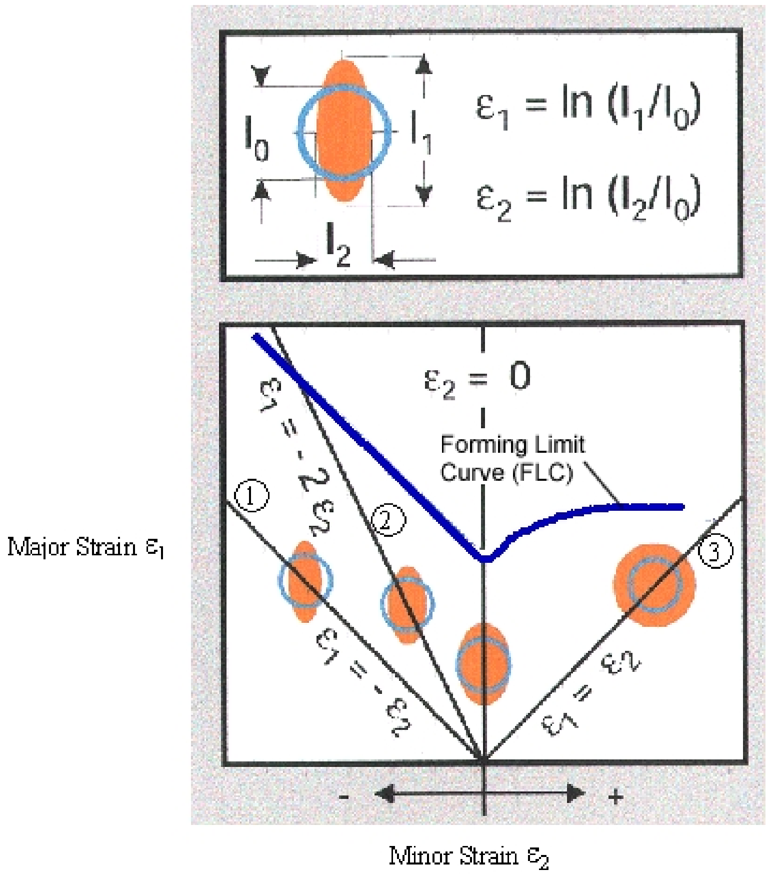


Figure 7.1.1-1 Forming Limit Diagram

Drawn sheet-metal parts, with plastic strains that are located below the Forming Limit Curve (FLC), lead to feasible parts. On the other hand, parts where the plastic strains are located above the FLC will result in failure.

Tubular hydroforming simulations included tube manufacturing, pre-bending, pre-forming and the final hydroforming .

7.1.2 Strain Path Effect on the Forming Limit Curve

The Forming Limit Diagram in figure 7.1.1-1 is valid for a proportional deformation path $\varepsilon_1/\varepsilon_2$=constant like in the stamping process. The deformation path in the entire tube hydroforming process is non-proportional because of the pre-bending, pre-forming and the final hydroforming process.

In the FLD (figure 7.1.1-1) there are three auxiliary lines, which describe the ideal deep drawing (1), the uniaxial stretching (2) and the biaxial stretching (3). These lines classify the FLD into deep drawing and stretch drawing.

Compared with the proportional FLC there is a displacement to higher values if, for instance, the deformation path changes from uniaxial stretch (2) to biaxial stretch (3). There is a displacement of the FLC to lower values if there is a change from biaxial stretch (3) to uniaxial stretch (2). Combined deformations with different forming paths' than the ones mentioned above will result in FLD's with positions between those limits.

In this Engineering Report, the FLCs are determined with proportional deformation pathes (e.g. Nakazima method). As a result of the FLD, it is not possible to predict failure in the non-proportional tubular hydroforming process.

Due to this fact, there are no FLD's shown for the tubular hydroforming process in this Engineering Report.

Forming of the straight tube from a flat sheet is the first simulation step for the tubular hydroforming process.

7.2 Tubular Hydroforming

Currently, there is no complete accurate way to simulate the forming of these parts The simulations were not used for tool development, but were done in parallel, or sometimes after the tool development had been completed. The time required to complete the simulations and the lack of confidence in the results are issues that have limited the usefulness of the forming simulations for tubular hydroformed parts. The existing software does offer some tools to initially evaluate the product design and futher optimize the use of material.

Two types of forming simulations were done on the Front Door Hinge Tube and the Front Door Latch Tube. A one-step simulation was preformed by an ULSAC Consortium member company. The incremental simulation was made by Krupp Drauz GmbH, who was also the manufacturer of the hinge and latch tubes.

The first step was the forming of a flat sheet to a tube. There are two possibilities simulating this process. The first variant is to simulate the tube manufacturing by defining nodal point displacements of each node of a flat steel sheet. There was no tool geometry used for this step. As a result of those nodal point displacements there is a tube geometry created, which has a longitudinal slot. The “joining process” is simulated by linking the nodes along the longitudinal slot. This variant was used in the incremental tubular hydroforming simulation performed in the ULSAC Program.

Another possibility is to simulate the tube manufacturing by two rolls. The flat steel sheet is placed in a tangential position to the first roll. The second roll moves around the first roll with the flat steel sheet in between. This movement results in a tube geometry. The longitudinal slot is joined by linking the nodes.

Both variants, which are special stand alone tools in the INDEED™ software, result in a small change of the mechanical material properties, which were transferred into the pre-bending process simulation.

Due to the rigid body of the tool, it was unnecessary to use values for the material of the tools. The material used for the Latch- and Hinge Tube was high strength steel with minimum yield strength of 280 MPa. The calculations have been done with an elastic-plastic anisotropic model for the material behavior.

Pre-bending is the second step in the tubular hydroforming process.

7.2.1 Hinge Tube

7.2.1.1 Incremental Simulation

7.2.1.1.1 Pre-bending Simulation

The second operation is the pre-bending of the tube. This was done with a conventional bending tool. In the simulation the tooling boundary conditions, the inner and outer mandrel, were used as input data. The tube was located between those two mandrels during the pre-bending process.

The thinning and thickening at the outer and inner bending radius of the pre-bent Hinge Tube with an initial material thickness of 1.2mm is shown in figure 7.2.1.1.1-1. The simulation results show thinning at the outer radius of the tube of about 16% - 19% and thickening at the inner radius of approximately 21%.

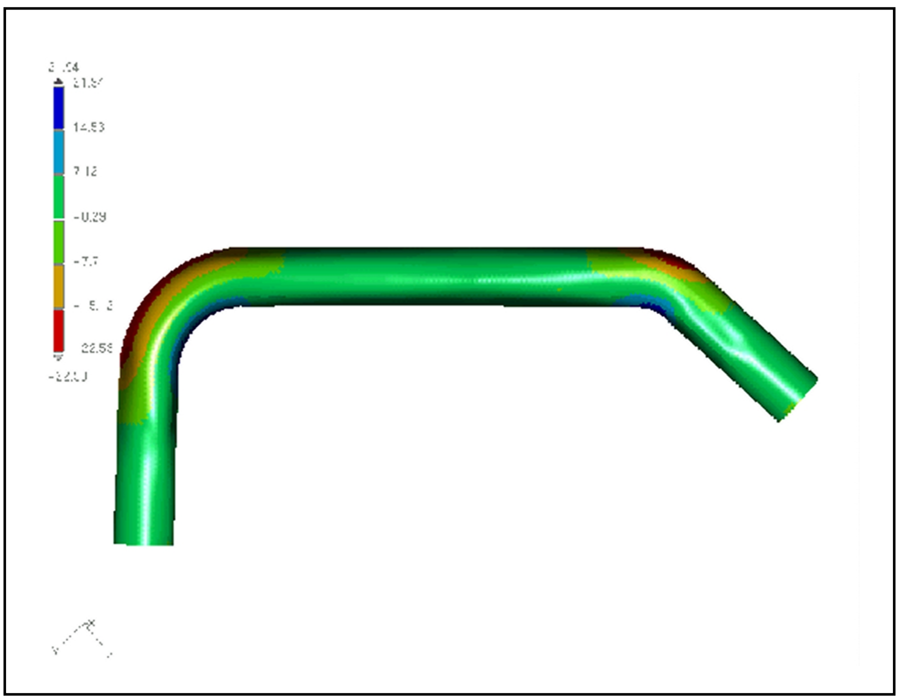


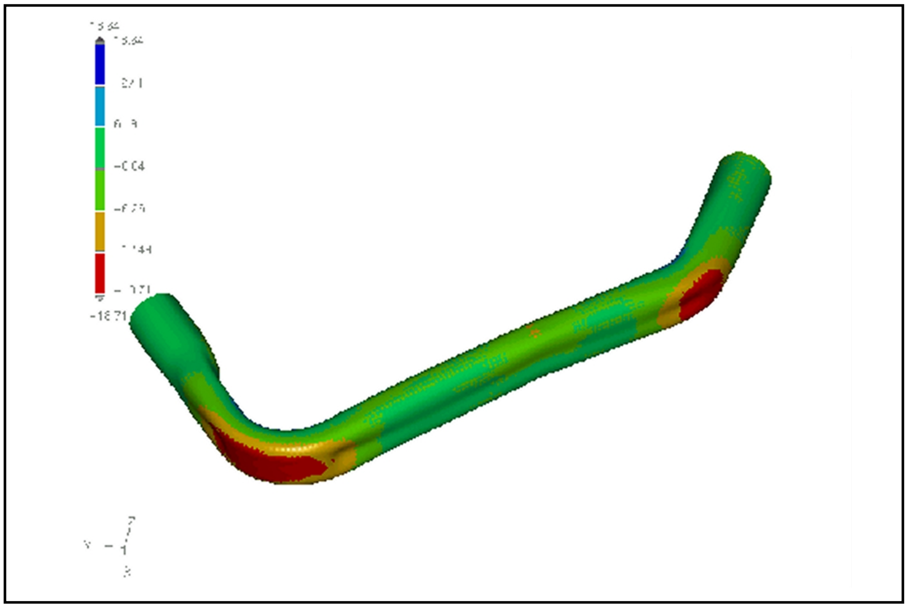
Figure 7.2.1.1.1-1 Pre-bent Hinge Tube

The tube was preformed to get a starting geometry that fits into the hydroforming tool.

7.2.1.1.2 Pre-forming Simulation

Pre-forming is necessary to bring the pre-bent tube into a shape that will fit into the hydroforming tool. The pre-forming tools were described as rigid bodies.

Figure 7.2.1.1.2-1 and 7.2.1.1.2-2 shows the thinning and thickening of the tube after the pre-forming operation.



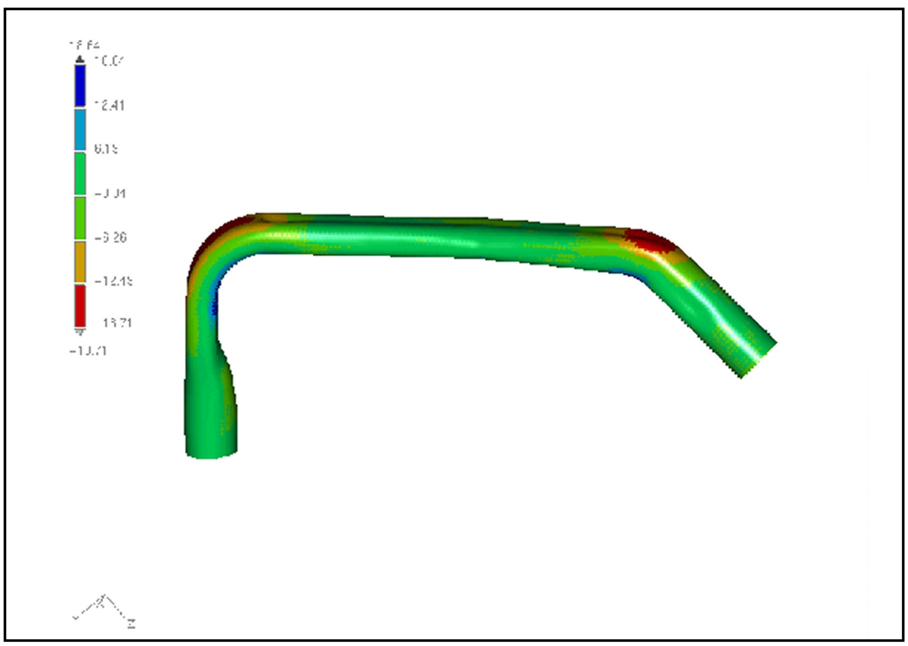


Figure 7.2.1.1.2-1 & 7.2.1.1.2-2 Pre-formed Hinge Tube

Due to the pre-forming operation of the hinge tube there is an increase of thinning at the outer radius to approximately 17-18.5%. The design of the pre-forming tool leads to tensile stresses on the inner radius of the tube. This effect causes the material thickening to decrease from 21% (bending operation) to about 16%.

7.2.1.1.3 Hydroforming Simulation

The pre-forming tube was placed into the hydroforming tool. The tool was closed and then internal pressure increased. The tool force during the process was constant. During the simulation the tool was held in position after it was closed. There was no force control of the tools during the simulation.

In figure 7.2.1.1.3-1 and 7.2.1.1.3-2, thinning and thickening of the final hydroformed Hinge Tube is shown. The forming simulation predicted that the local expansion in the 90°-bending radius is a critical area for failure. After the pre-bending and pre-forming operations, additional thinning due to the hydroforming operation without axial feeding occurs. This results in thinning in the outer 90°-bending radius of about 34%.

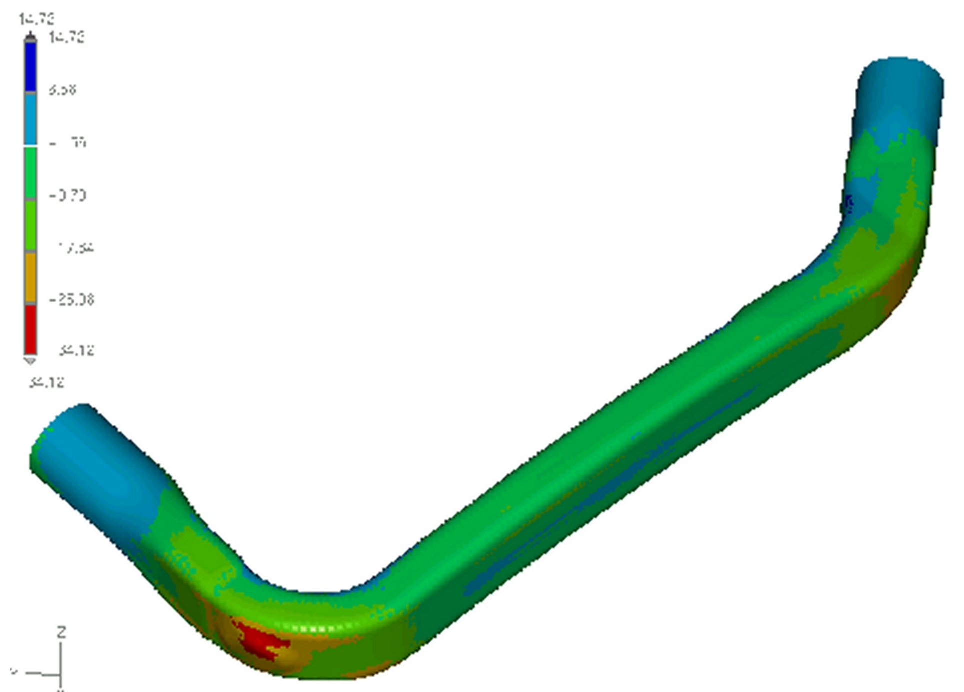


Figure 7.2.1.1.3-1 Final hydroformed Hinge Tube

One-step simulation is a part simulation that is done without the tool geometry.

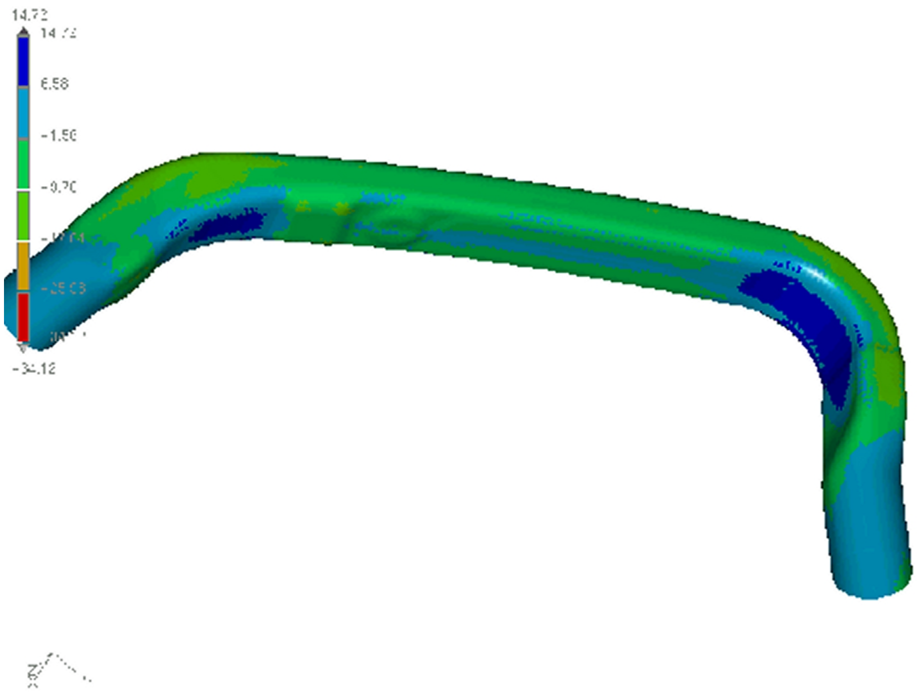


Figure 7.2.1.1.3-2 Final hydroformed Hinge Tube

The final hydroforming process once again reduces the material thickening on the inner side of the 90°-bending radius from 16% to 13%.

7.2.1.2 One-Step Simulation

The one-step simulation is a part simulation that is done without the tool geometry. There are two possibilities for calculating thinning and thickening of the hydroformed components. Thinning and thickening can be calculated by mapping back the final hydroformed components to the straight tube. This simulation type includes the thinning and thickening effects of the hydroforming and pre-bending process in the calculation. In the second simulation type, material thinning and thickening are calculated by mapping back the hydroformed tube to a pre-bent tube. This calculation includes the thinning and thickening effects of the hydroforming process only. In both calculation methods, axial feeding can be considered by varying the starting length of the straight tube.

The ULSAC Front Door Hinge Tube one-step simulation was calculated by mapping back the hydroformed component to the straight tube. Figure 7.2.1.2-1 shows the calculated thinning and thickening values for the Front Door Hinge Tube. The scale represents the change of wall thickness in percent. On this scale, 1.00 is equal to 100% which corresponds to the starting wall thickness of 1.2 mm. The simulation indicates the outer 90°-bending radius as a critical area of failure with a maximum thinning of 20% (0.80) and a maximum thickening on the inner side radius of 10% (1.10).

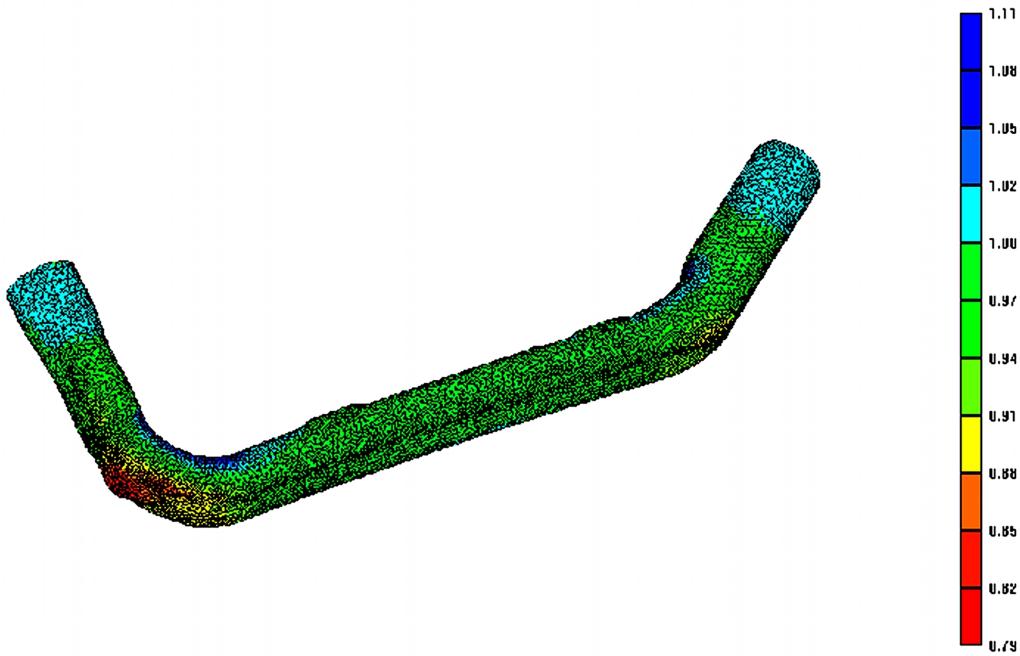


Figure 7.2.1.2-1 Front Door Hinge Tube One-step Simulation

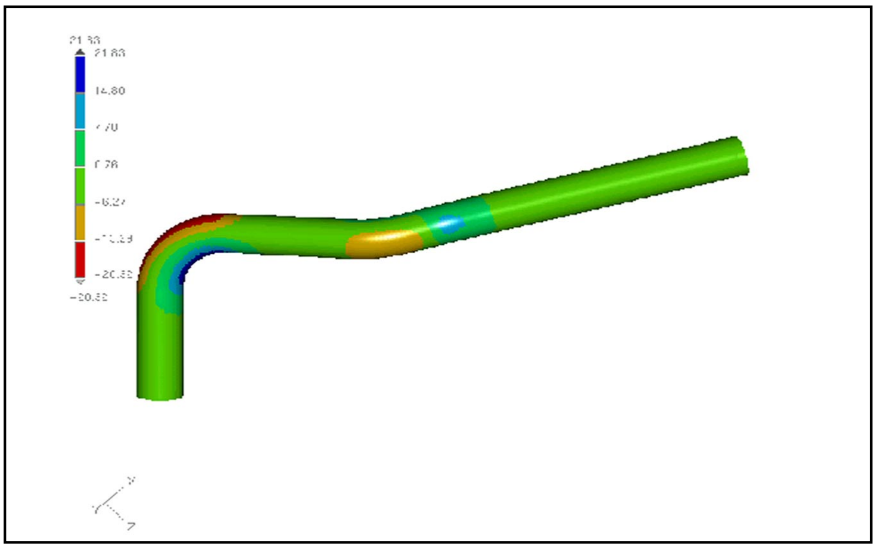
The inner and outer mandrel were taken into consideration for the pre-bending simulation.

7.2.2 Latch Tube

7.2.2.1 Pre-bending Simulation

As already mentioned, the inner and outer mandrel were taken into consideration for the pre-bending simulation and the tube was located between those two mandrels during the bending process.

The forming simulation of the Latch Tube is shown in the figures 7.2.2.1-1 and 7.2.2.1-2 illustrating the thinning and thickening of the pre-bent Latch Tube.



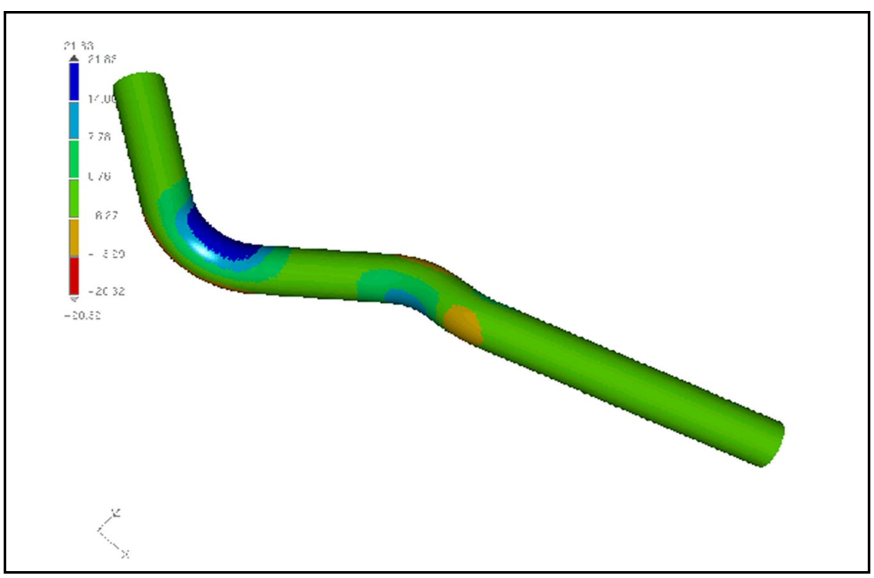


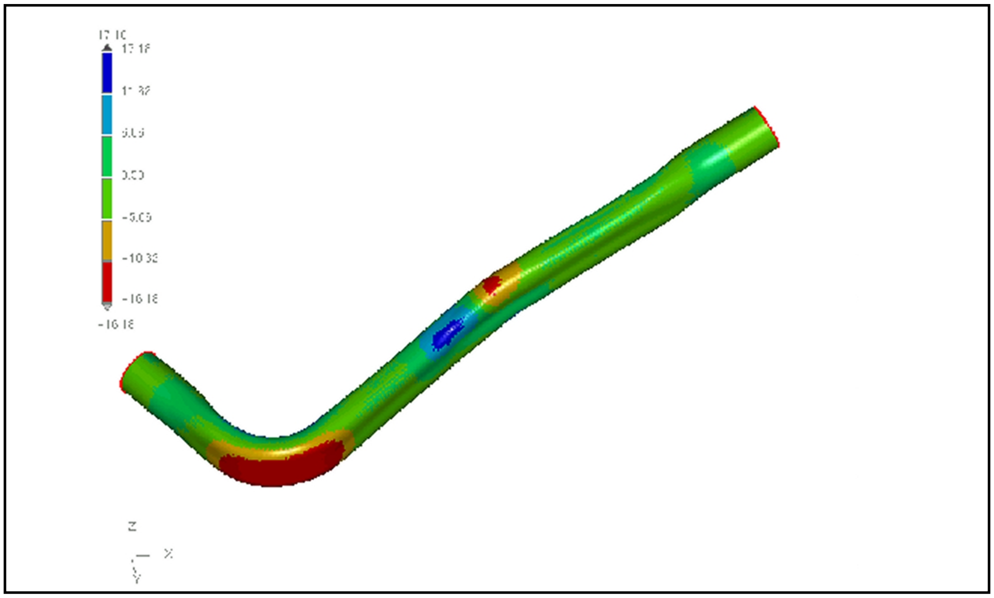
Figure 7.2.2.1-1 & 7.2.2.1-2 Pre-bent Latch Tube

The pre-forming simulation on the Latch Tube leads to a thinning in the middle of the part of about 15%.

According to the forming simulation there is a decrease of wall-thickness on the outer radius of the pre-bent tube of about 14%. The starting wall-thickness is 1.0mm. The bending operation leads to a thickening on the inner radius of about 20%.

7.2.2.2 Pre-forming Simulation

The material thinning and thickening as a result of the pre-forming simulation are shown in the figures 7.2.2.2-1 and 7.2.2.2-2.



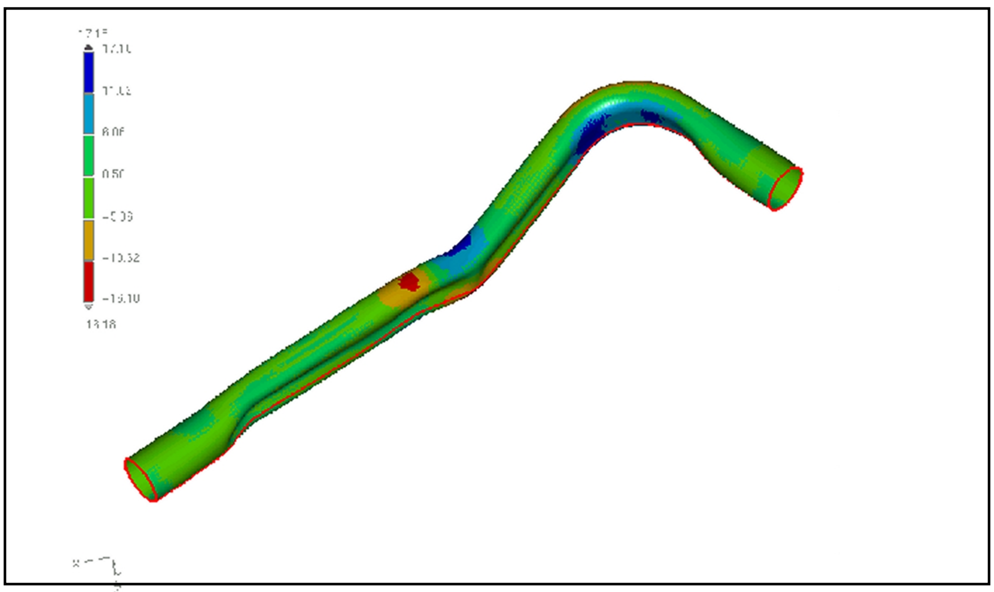


Figure 7.2.2.2-1 & 7.2.2.2-2 Pre-formed Latch Tube

Performing these forming simulations, areas of thinning and thickening can identify critical areas.

The pre-forming operation leads to a thinning in the middle of the part of about 15%. The design of the pre-forming tool causes tensile stresses on the inner 90°-bending radius. Due to these tensile stresses, the thickening in this area decrease from 20% to 12%, compared to the values in the pre-bending operation.

7.2.2.3 Hydroforming Simulation

The pre-forming tube was placed into the hydroforming tool. The tool was closed and then the internal pressure was increased. The tool force during the process was constant. During the simulation the tool was held in position after it was closed. There was no force control of the tools during the simulation.

Figures 7.2.2.3-1,-3 shows the simulation results of the final hydroforming process-step for the Latch Tube. Figure 7.2.2.3-1 points out that due to thinning of 33%, the outer 90°-bending radius is a critical area of failure. Also the material thinning of 27% in the middle part of the Latch Tube predicts a critical area of failure.

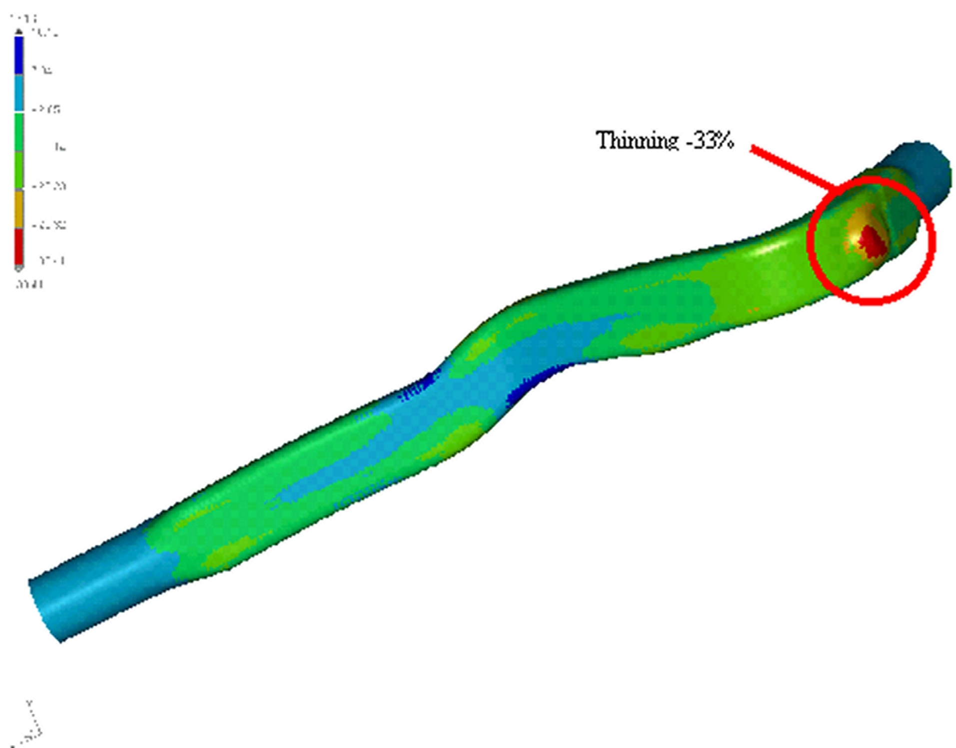


Figure 7.2.2.3-1 Final hydroformed Latch Tube

As a result of the forming simulation, minor design changes were made to make the part feasible to manufacture.

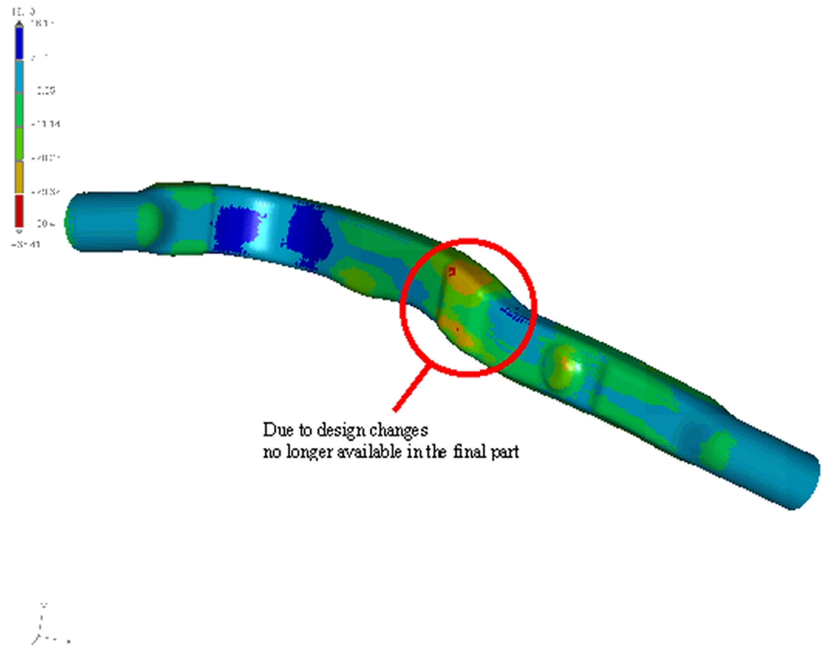


Figure 7.2.2.3-2 Final hydroformed Latch Tube

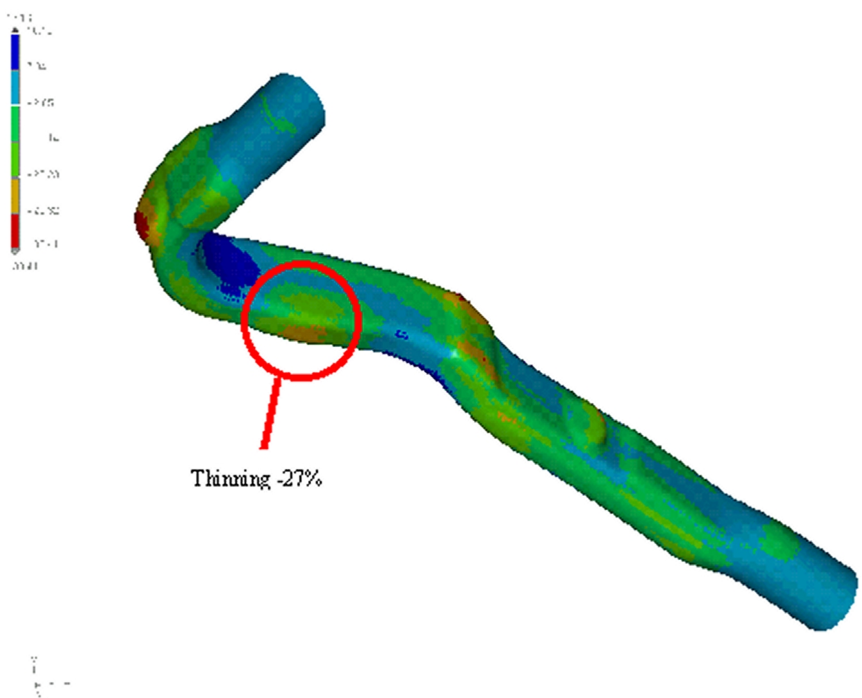


Figure 7.2.2.3-3 Final hydroformed Latch Tube

As a result of this forming simulation, minor design changes were made to the part design in the identified predicted area of failure (see Figure 7.2.2.3-2) to make the part feasible to manufacture.

7.2.2.4 One-Step Simulation

The one-step forming simulation identified three critical areas of failure on the Latch Tube. First (1), there is the outer 90°-bending radius where thinning of 23% occurs. The second (2) is the middle area with local thinning of 20%. The third (3) critical area of failure occurs where a material bulge forms a 30% thinning. This calculated failure occurs because the tool geometry is not taken into account in the one-step simulation.

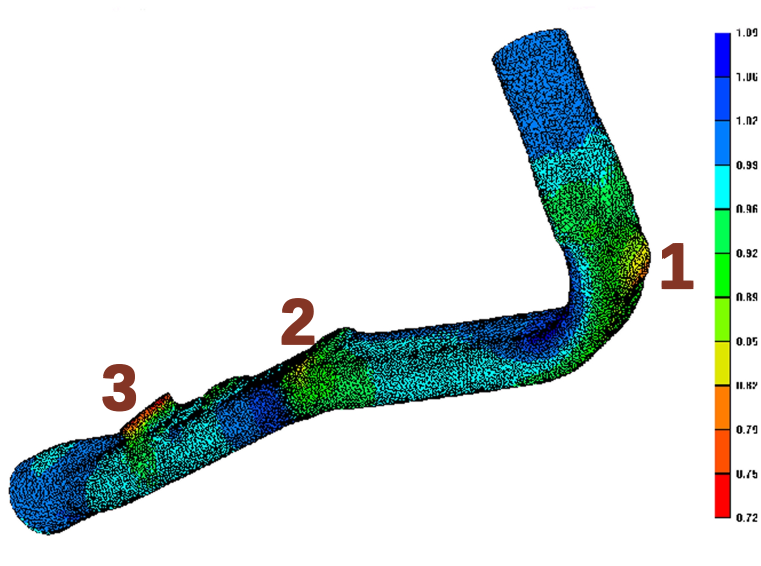


Figure 7.2.2.4-1 Front Door Latch Tube One-step Simulation

7.3 Stamping

Stamping simulations for the Door Panel Outer, the Panel Front Door Inner Front, the Panel Front Door Inner Rear and the Mirror Flag were performed using PAMSTAMP™, an explicit dynamic software.

7.3.1 Panel Front Door Inner Front

The Panel Front Door Inner Front is described as a tailor welded blank (1.0/1.2mm) with the material grade 140 MPa. A metal thinning contour plot after simulating stamping is shown in Figure 7.3.1-1. The maximum thinning (32.2%) occurred in the lance area in the upper half of the TWB (1.0mm) due to material draw in. This area was located outside the trim area. Also in the upper half of the TWB, material thinning of 22% was calculated in the contour of the radius at the deepest point of draw. This was calculated as a critical area of failure in the stamping process. In the lower half of the TWB (1.2mm) 28% thinning was calculated on the lower edge of the forming shape.

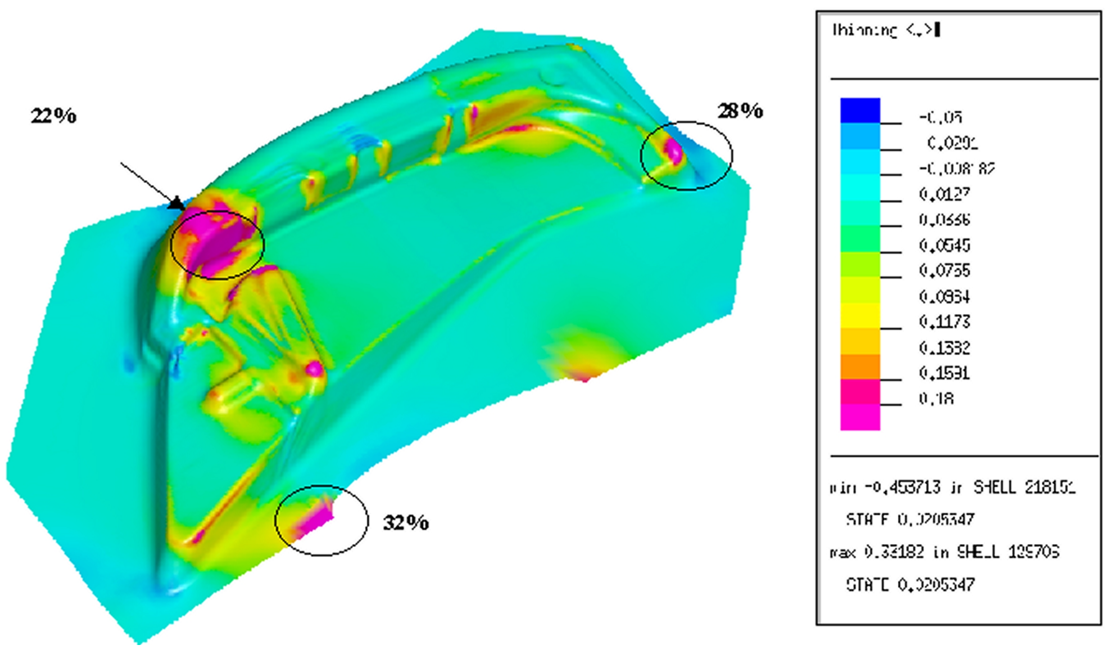


Figure 7.3.1-1 Panel Front Door Inner Front

Areas of the TWB where strains approached the marginal failure limits were in the trim area of the upper half of the TWB. .

Forming Limit Diagrams for the Panel Front Door Inner Front are shown for the upper half of the tailor welded blank (1.0mm) in figure 7.3.1-2 and for the lower half of the tailor welded blank (1.2mm) in figure 7.3.1-3. Areas of the part where strains approached the marginal failure limits were in the trim area of the upper half of the TWB. Therefore, the part was considered formable.

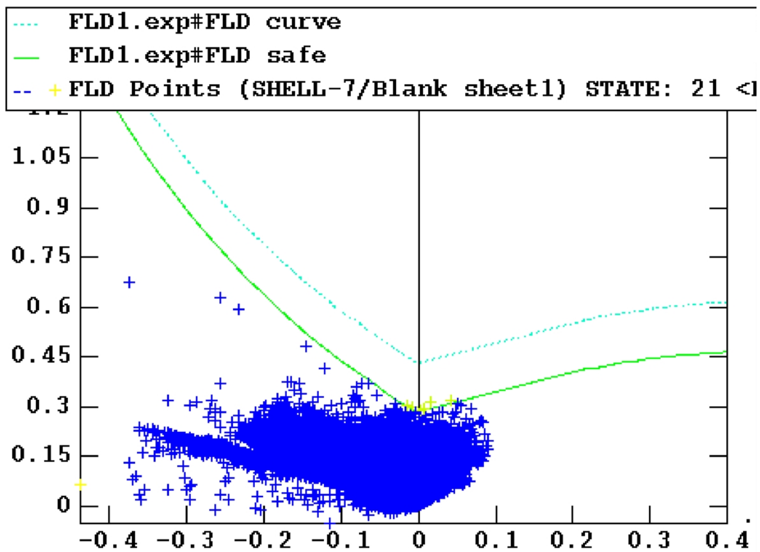


Figure 7.3.1-2 FLD for the upper half of the Panel Front Door Inner Front

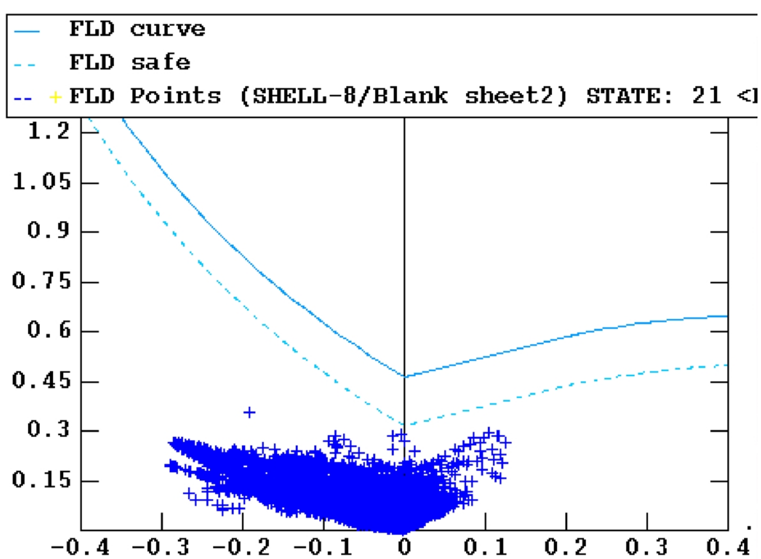


Figure 7.3.1-3 FLD for the lower half of the Panel Front Door Inner Front

The Panel Front Door Inner was simulated with a sheet thickness of 0.6mm and a material grade of 140 MPa.

7.3.2 Panel Front Door Inner Rear

The Panel Front Door Inner Rear was simulated with a sheet thickness 0.6mm and a material grade of 140 MPa. The material thinning after stamping is shown in the material contour plot, Figure 7.3.2-1.

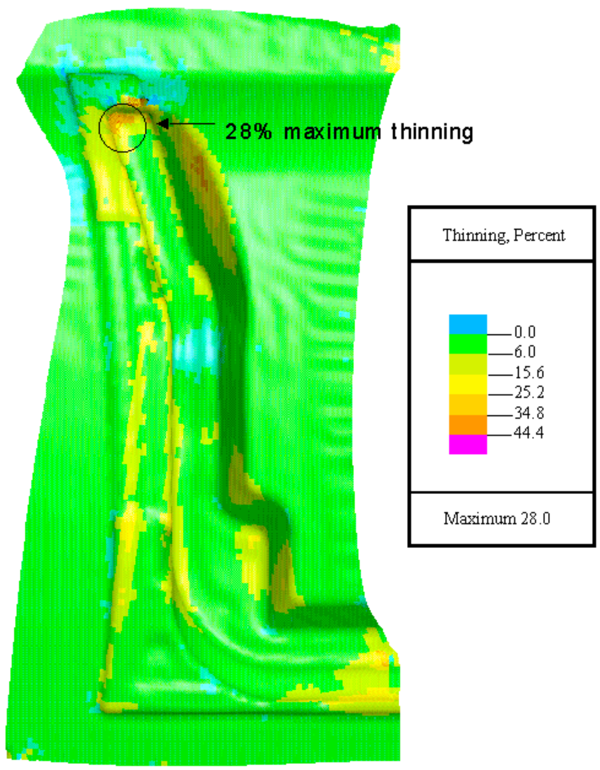


Figure 7.3.2-1 Panel Front Door Inner Rear

The maximum thinning was about 28%, which occurred along the contour of the radius near the top of the Panel Front Door Inner Rear.

The FLD for the Panel Front Door Inner Rear stamping operation show that this part can be stamped without splitting.

The FLD for the Panel Front Door Inner Rear stamping operation is shown in figure 7.3.2-2. The simulation results show that this part can be stamped without splitting.

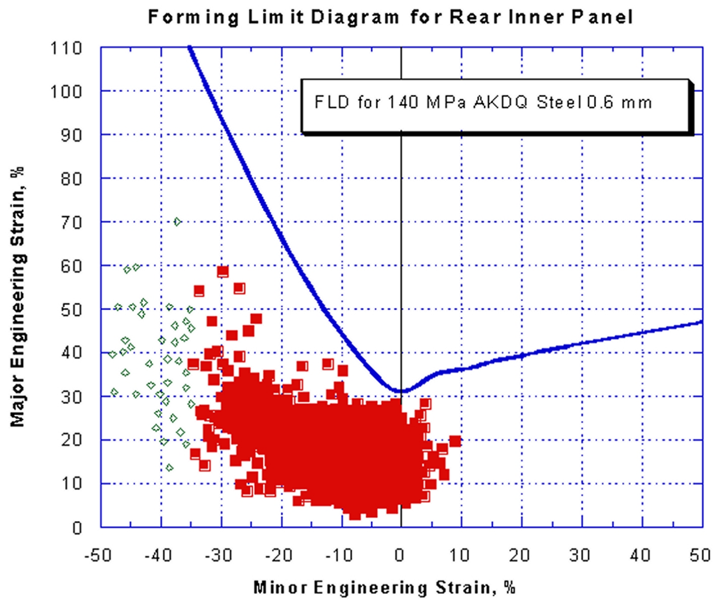


Figure 7.3.2-2 FLD for the Panel Front Door Inner Rear

7.3.3 Panel Mirror Flag Outer

The forming simulation of the Mirror Flag was done with a material grade 140 MPa and a sheet thickness of 1.0mm. The results which are shown in figure 7.3.3-1 point out that a maximum thinning of 21.6% after stamping occurred along the contour of the radius at the deepest point of draw.

The Panel Mirror Flag simulation predicted that the part could be feasible to manufacture.

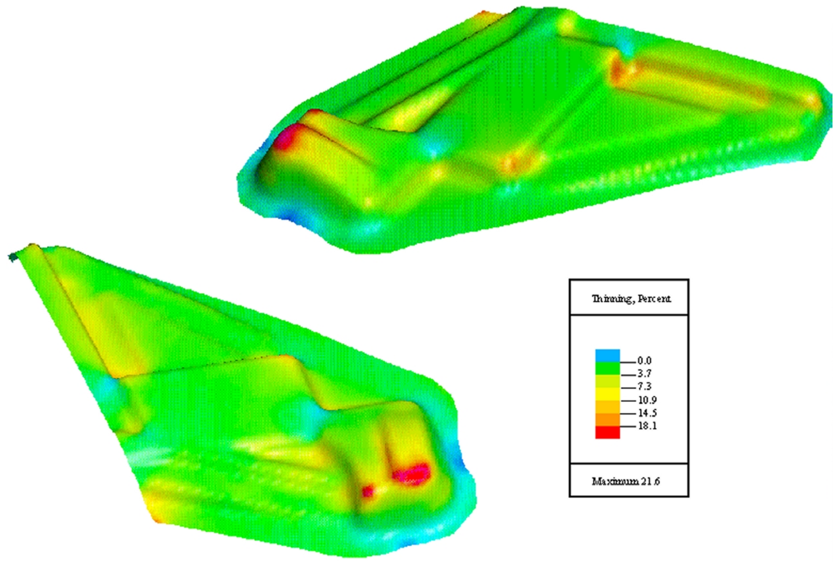


Figure 7.3.3-1 Mirror Flag

The forming limit diagram (FLD) for the Mirror Flag stamping operation is shown in figure 7.3.3-2. The FLD shows that the part could be manufactured successfully well within forming limit constraints.

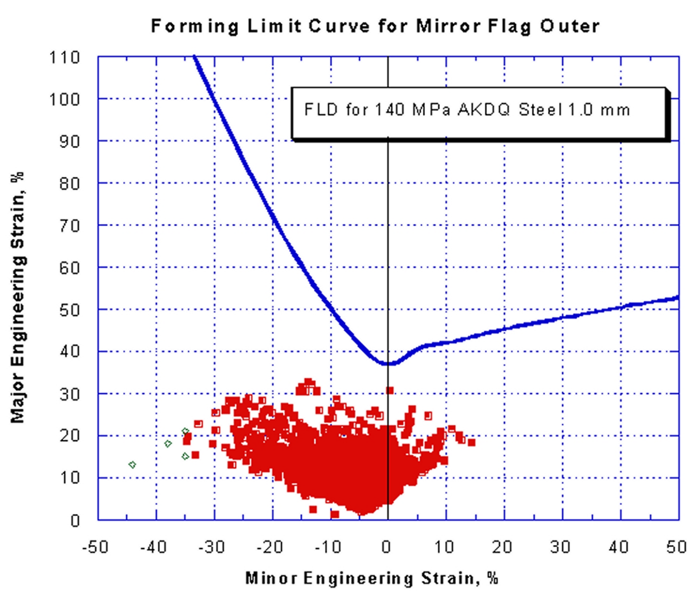


Figure 7.3.3-2 FLD for the Mirror Flag

7.3.4 Panel Front Door Outer

The forming simulation of the Panel Front Door Outer was performed using AUTOFORM™. This FEM-software is an incremental, non-linear, implicit FEM-program. The flat sheet was created with membrane elements.

Because of the rigid body element representation of the tool it was not necessary to use material data. With the selected friction coefficient and the tool stiffness as input parameters, the tool was considered a steel tool in the simulation.

Two simulations were performed for the Panel Front Door Outer -- first with DP600 (0.6mm) and then with BH260 (0.7mm). DP600 with the material thickness of 0.6mm was simulated as the most difficult to form.

The calculations have been done with the Hill-model for the material behavior. The simulated blank holder force for both materials was 180 tons.

Figure 7.3.4-1 and Figure 7.3.4-2 show the plastic strain for the Panel Front Door Outer in both material types and grades. The forming simulation predicts that the Panel Front Door Outer can be manufactured without failure. Detail analysis showing material thinning in critical areas in shown in Figure 7.3.4-3 and Figure 7.3.4-4.

The incremental forming simulation of the Panel Front Door Outer with material DP600 (see Figure 7.3.4-1) shows that the part is feasible to manufacture. Therefore, it can be assumed that all other materials and thicknesses selected for use in the ULSAC program should be feasible to manufacture as well.

The simulations calculated plastic strain of 1.6% for DP600 (0.6mm) in the middle area of the Panel Front Door Outer and 1.3% for the BH260 (0.7mm).

To verify the feasibility of the other materials, an additional simulation was done with the material BH260 (0.7mm). The plastic strain contour plot of the Panel Front Door Outer is shown in Figure 7.3.4-2.

Plastic strain of the Panel Front Door Outer were shown to predict stretch due to forming .

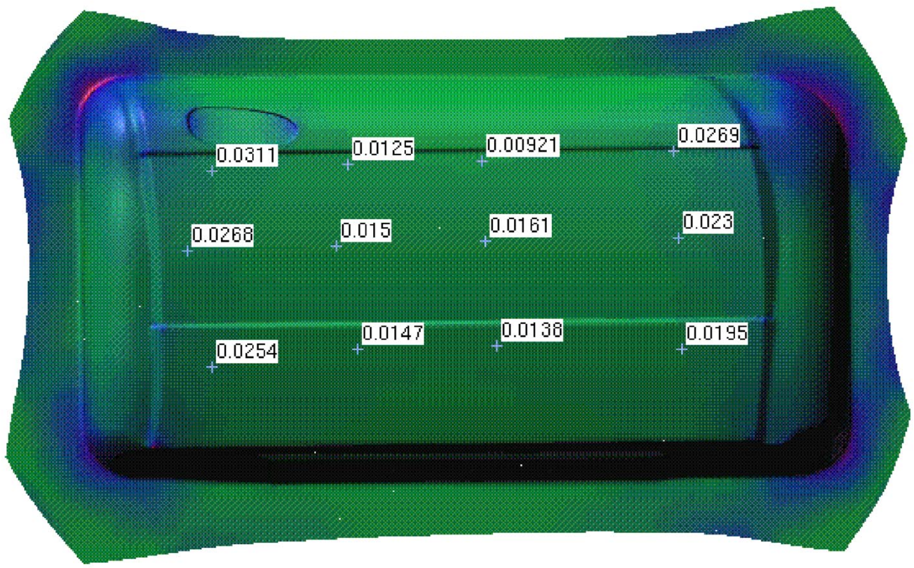


Figure 7.3.4-1 Panel Front Door Outer Simulation DP600

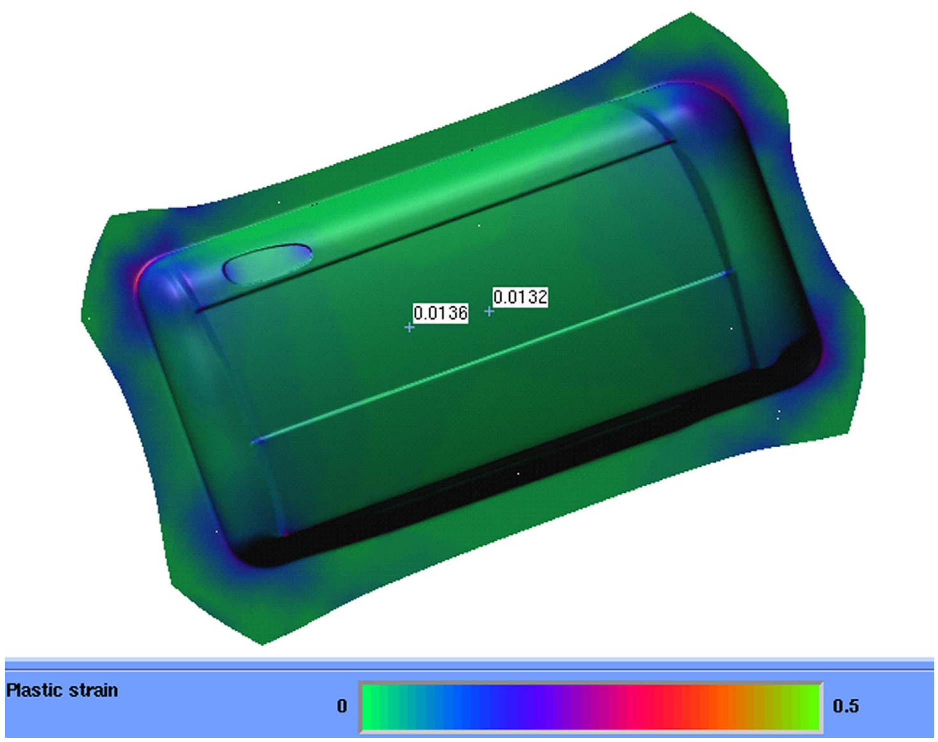


Figure 7.3.4-2 Panel Front Door Outer Simulation BH260

The critical areas of forming in the Panel Front Door Outer occur at the edge of the upper and lower left corners.

The simulation also shows two critical areas for forming on the Panel Front Door Outer with material BH260 presented in detail in figures 7.3.4-3 and 7.3.4-4. Thinning was calculated to predict critical areas of failure.

One critical area occurs at the upper left corner at the edge of the forming shape and the upper feature line. The stamping processes leads to a thinning of 18%.

Figure 7.3.4-3 Panel Front Door Outer upper left corner thinning

The simulations indicate thinnings of 18% and 19% in the areas of critical failure on the Panel Front Door Outer.

The other critical area occurs on the lower left corner of the forming shape indicating thinning of 19%.

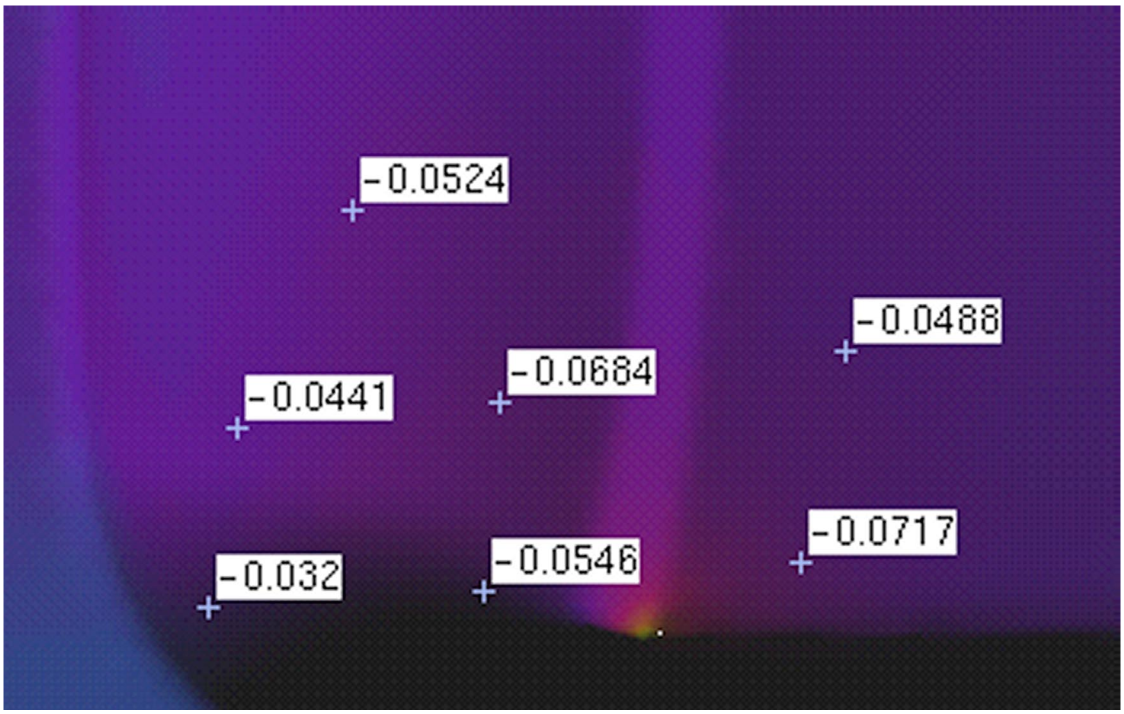


Figure 7.3.4-4 Panel Front Door Outer lower left corner

The simulation verified that the Panel Front Door Outer could be manufactured successfully.

A forming limit curve for a material grade BH260 was used to verify the feasibility of the Panel Front Door Outer. The result of the forming simulation is shown in the forming limit diagram (FLD), Figure 7.3.4-4. The simulation predicted that the part can be manufactured.

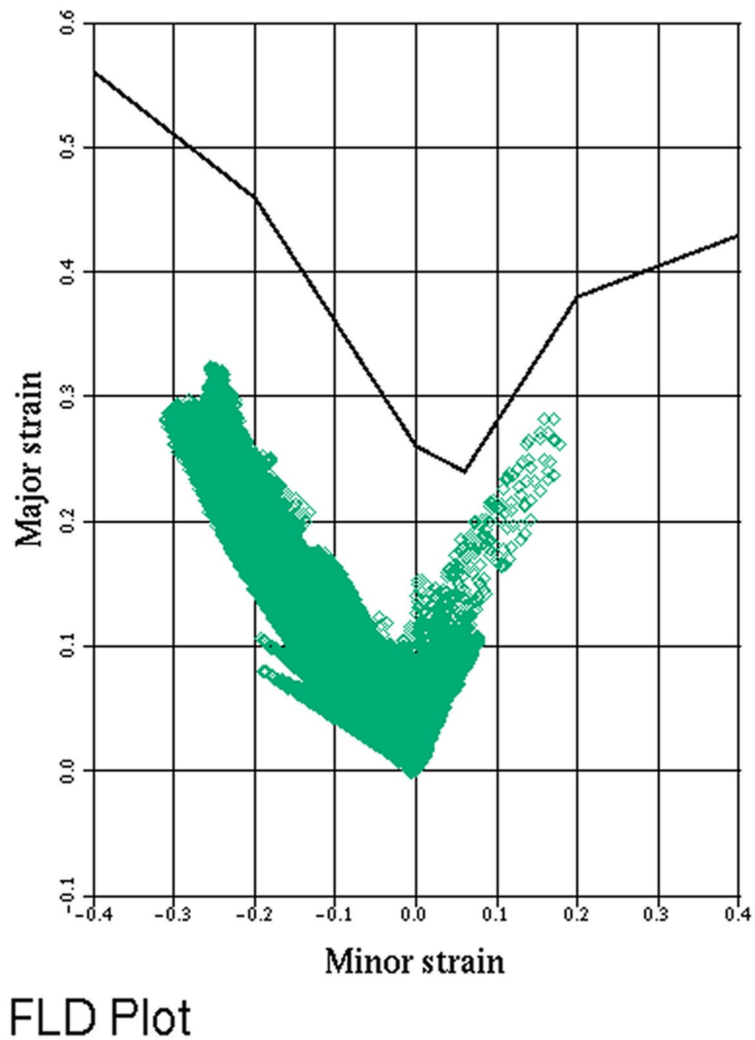


Figure 7.3.4-4 FLD for the Panel Front Door Outer

7.4. Conclusions

Forming simulation is a predictive tool, which helps designers optimize the part and tool design. The incremental process simulation is very helpful to predict plastic strain, material thinning, wrinkling and material failure, as well as to optimize the tool design in a timely and cost-efficient manner. Nevertheless, the knowledge of the material, the manufacturing process and the simulation program is critical in interpreting the results of a forming simulation. Otherwise, wrong conclusions may be drawn from forming simulations, especially in one-step simulations.

Forming Simulation could also be used to predict manufacturing feasibility when slight material grade changes are applied within one type of material. For this type of forming simulation, it is imperative that the FLCs for the substituted material at the chosen material thickness are available as delivered to the press shop.

8 Parts Manufacturing

Manufacturing experience of 'production intent' prototypes was one of the main criteria in supplier selection.

Background

The first step in parts manufacturing was to select suppliers. The main criteria for supplier selection was to keep in mind that parts should be production representative. Experience with manufacturing "production intent" prototypes was one of the main criteria in supplier selection.

Other criteria for final supplier selection were:

- Major OEM quality rating or ISO-9001 certification
- Available capacity for program
- Manufacturing process corresponds to the program timing
- Experience in production representative prototyping
- Preparedness to enter simultaneous engineering prior to contract
- CAD/CAM systems compatible with CATIA
- Cost competitive

8.1 Part Supplier Selection

Based on the criteria for supplier selection and PES' experience with tool & parts manufacturers and assembly of the ULSAB body structure, the following companies were selected:

- Stamping parts - Stickel GmbH, leading supplier to Porsche AG
- Tubular hydroformed parts - Krupp Drauz GmbH, supplier to General Motors, DaimlerChrysler AG, Audi AG
- Assembly, Laser welding - Porsche AG, R&D Center Weissach

Stickel GmbH and Krupp Drauz GmbH were chosen as part manufactures because of their experience and location.

Company Name	Address	Number of Employees
Stickel GmbH	Porschestrasse 2, D-74369 Loechgau	40
Major Products		
	Prototype Building Prototype Tooling, Prototype Stamping Low Volume Production Stampings and Subassemblies	
Other Divisions	Customers	Major Equipment
None	Audi AG BMW AG Mannesmann AG DaimlerChrysler AG Opel AG Porsche AG	Presses up to 800 tons Bed size up to 2m x 3m 3D Laser CMM Equipment CATIA CGS

Company Name	Address	Number of Employees
Krupp Drauz GmbH	Weipertstrasse 37, D-74076 Heilbronn	850
Major Products		
	Tube- and Sheet Hydroforming Prototype Build Prototype and Series Tooling Low and Middle Volume Production of Parts	
Other Divisions	Customers	Major Equipment
Jigs and Fixtures Deep Drawings Tool Making Assembly Lines	Audi AG DaimlerChrysler AG Volkswagen AG General Motors	Hydroforming Presses High Speed Milling 6kW- Laser

Figure 8.1-1 Supplier Information

In order to optimize design, suppliers and assembly specialists conducted program reviews on a regular basis.

Stickel, Krupp Drauz GmbH is a supplier in partnership with Thyssen Automotive, The Budd Company, Fabco and Krupp Camford. Due to this technology partnership there is high experience available concerning the serial production of tubular hydroformed parts.

Due to experience and latest available equipment in laser welding and MAG welding, Porsche's R&D Center in Weissach was chosen for the assembly of the parts.
Because of the high quality stamped parts supplied for the ULSAB program, Stickel was chosen in the ULSAC program as well. Furthermore due to their close locations, Stickel, Krupp Drauz and Porsche's R&D Center were able to work together most productively.

8.2 Simultaneous Engineering

In order to achieve the optimal design from a manufacturing and assembly standpoint, program reviews were held between the part suppliers and the assembly specialists. A final design review was held prior to final drawing release.

Each supplier had specialists in CAD/CAM, tool design, and manufacturing present at the design review. Every detail of the part was reviewed for issues such as formability, spring back, tolerance control and assembly. Representatives of steel companies also attended these reviews to discuss and resolve material-related issues.

At the beginning of the manufacturing process, forming simulations of each part were performed with available material data provided by member companies of the ULSAC Consortium. These simulations indicated that the parts were either feasible to manufacture or it was necessary to make design changes.

Simultaneous engineering allowed necessary changes to be made prior to drawing release for tool design.

During parts manufacturing, representatives of PES coordinated materials supply for parts manufacturing and gathered circle grid strain analysis data to compare with forming simulation results. PES also coordinated timing according to the ULSAC Program Timeline.

In this simultaneous engineering process, part suppliers and PES worked together and all parts were manufactured successfully and on time.

Three different hydraulic presses had to be used for the stamped parts of the ULSAC door structure because of the material grade and blank size.

8.3 Press Environment

8.3.1 Stamping

Three different hydraulic presses were used for the stamped parts of the ULSAC door related to the material grade and part dimensions. The part information, the tool environment and the press parameters are shown in the following tables.

The Panel Front Door Inner Front and the Panel Front Door Inner Rear were stamped on a 500-ton press with a bed size of 1250 x 2000mm. The Mirror Flag and the Reinforcement Latch were stamped on a 250-ton press with a bed-size of 1000 x 1500mm.

“Soft”-tools, which consist of a punch, die, and a blankholder, were used because of the mild steel chosen for these parts.

Stickel provided press parameters for the stamped parts.

PART INFORMATION

Customer:	ULSAC	**Program Name:**	Validation Phase
Part Name:	Panel Front Door Inner Rear	**Production Location:**	Stickel
Part Number:	3004		
Blank Size:	1100x600mm		

TOOL INFORMATION

Tool Material:	Soft-tool	**Process:**	Stamping
Tool Built Source:	Stickel		

PRESS PARAMETERS

PRESS		
Identification:	Hydraulic press/Eifel 500 ton	
Bed Size:	1250x2000mm	
BLANKHOLDER		
Force (ton):	80	
DRAW LUBRICATION		
Type	**Application**	**Relative Amount**
Platinol BZK3	roller	large

PART INFORMATION

Customer:	ULSAC	**Program Name:**	Validation Phase
Part Name:	Panel Front Door Inner Front (TWB)	**Production Location:**	Stickel
Part Number:	3008		
Blank Size:	1500x800mm (900x800/600x800)		

TOOL INFORMATION

Tool Material:	Soft-tool	**Process:**	Stamping
Tool Built Source:	Stickel		

PRESS PARAMETERS

PRESS		
Identification:	Hydraulic press/Eifel 500 ton	
Bed Size:	1250x2000mm	
BLANKHOLDER		
Force (ton):	130	
DRAW LUBRICATION		
Type	**Application**	**Relative Amount**
Platinol BZK3	roller	large

All material for the ULSAC door was normal series production steel representing widely available material.

PART INFORMATION

Customer:	ULSAC	**Program Name:**	Validation Phase
Part Name:	Panel Mirror Flag Outer	**Production Location:**	Stickel
Part Number:	3020		
Blank Size:	600x600mm		

TOOL INFORMATION

Tool Material:	Soft-tool	**Process:**	Stamping
Tool Built Source:	Stickel		

PRESS PARAMETERS

PRESS		
Identification:	Hydraulic press/SMG 250 ton	
Bed Size:	1000x1500mm	
BLANKHOLDER		
Force (ton):	110	
DRAW LUBRICATION		
Type	**Application**	**Relative Amount**
Platinol BZK3	roller	large amount

PART INFORMATION

Customer:	ULSAC	**Program Name:**	Validation phase
Part Name:	Reinforcement Latch	**Production Location:**	Stickel
Part Number:	3030		
Blank Size:	200x150mm		

TOOL INFORMATION

Tool Material:	Soft-tool	**Process:**	Stamping
Tool Built Source:	Stickel		

PRESS PARAMETERS

PRESS		
Identification:	Hydraulic press/SMG 250 ton	
Bed Size:	1000x1500mm	
BLANKHOLDER		
Force (ton):	110	
DRAW LUBRICATION		
Type	**Application**	**Relative Amount**
Platinol BZK3	roller	large amount

Figure 8.3.1-1 Press Parameters

High strength materials used on the Panel Front Door Outer made it necessary to design the blankholder in steel.

The high strength material and the blank size (1700 x 1050mm) of the Panel Front Door Outer made it necessary to use a press with a maximum force of 800 tons and a bed-size of 2000 x 3000mm.

Due to the high strength material grades used for the Panel Front Door Outer, the blankholder was constructed of steel. The die and the punch were steel-reinforced “soft”-tools (figure 8.3.1-1).

PART INFORMATION

Customer:	ULSAC	**Program Name:**	Validation Phase
Part Name:	Panel Front Door Outer	**Production Location:**	Stickel
Part Number:	3000		
Blank Size:	1700x1050mm		

TOOL INFORMATION

Tool Material:	Die: soft-tool Punch: steel-reinforced soft-tool Blankholder: steel	**Process:**	Stamping
Tool Built Source:	Stickel		

PRESS PARAMETERS

PRESS		
Identification:	Hydraulic press/Diefenbacher 800 ton	
Bed Size:	2000x3000mm	
BLANKHOLDER		
Force (ton):	85 - 400	
DRAW LUBRICATION		
Type	**Application**	**Relative Amount**
Platinol BZK3	roller	large

Figure 8.3.1-2 Press Parameters

8.3.2 Tubular Hydroforming

The hydroformed parts were manufactured on a 4000 ton Schuler Hydrap hydroforming press. The press was equipped with a bed size of 3200x2000mm. The maximum pressure which is feasible in this press for serial production is up to 2000 bar and for prototyping up to 3600 bar.

The internal pressure needed to hydroform the ULSAC components lead to high compressive loads per unit area and therefore, the tools had to be made of steel. Material feeding at the ends of the tube was made possible with the use of two axial cylinders.

The tubular hydroformed parts were manufactured by Krupp Drauz on a 4000 ton Schuler Hydrap hydroforming press.

PART INFORMATION

Customer:	ULSAC	**Program Name:**	Validation Phase
Part Name:	Front Door Hinge Tube	**Production Location:**	Krupp Drauz
Part Number:	3012		
Tube Size	48x1000x1.2		

TOOL INFORMATION

Tool Material:	steel	**Process:**	Tubular Hydroforming
Tool Built Source:	Krupp Drauz		

PRESS PARAMETERS

PRESS		
Identification:	Hydroforming press/Schuler Hydrap 4000 ton	
Bed Size:	3200x2000mm	
PRESS FORCE		
Force (ton):	1000	
INTERNAL PRESSURE		
Pressure (bar):	1700	
AXIAL FEEDING		
Cylinder 1 (mm):	20	
Cylinder 2 (mm):	40	
DRAW LUBRICATION		
Type	**Application**	**Relative Amount**
Gleitmo 2345 V (Fuchs Lubritc)	paintbrush	normal

PART INFORMATION

Customer:	ULSAC	**Program Name:**	Validation Phase
Part Name:	Front Door Latch Tube	**Production Location:**	Krupp Drauz
Part Number:	3014		
Tube Size	48x1000x1.0		

TOOL INFORMATION

Tool Material:	steel	**Process:**	Tubular Hydroforming
Tool Built Source:	Krupp Drauz		

PRESS PARAMETERS

PRESS		
Identification:	Hydroforming press/Schuler Hydrap 4000 ton	
Bed Size:	3200x2000mm	
PRESS FORCE		
Force (ton):	800	
INTERNAL PRESSURE		
Pressure (bar):	1500	
AXIAL FEEDING		
Cylinder 1 (mm):	11	
Cylinder 2 (mm):	13	
DRAW LUBRICATION		
Type	**Application**	**Relative Amount**
Gleitmo 2345 V (Fuchs Lubritc)	paintbrush	normal

Figure 8.3.2-1 Press Parameters

Circle grid strain analysis was performed to determine real strains or material thinning of the stamped parts.

8.4 Circle Grid Strain Analysis

8.4.1 Stamping Process

Circle grid strain analysis in the ULSAC program was performed to determine real strains or material thinning and material thickening of the three-dimensional stamped parts. Those measured strain and material thinning values were compared with the forming simulation results.

Corus NL Research & Development performed the circle grid strain analysis on the stamped parts. They are equipped with the latest system for strain measurement, called Phast, which is jointly developed by Geodelta and Corus NL Research & Development.

Phast is a vision-based measurement system that determines surface strains on formed sheet metal. The measurement errors are between ±0.5% (absolutely).

The first step was to apply a point circle grid pattern on the flat steel sheet by electro-chemical etching prior to the stamping process.

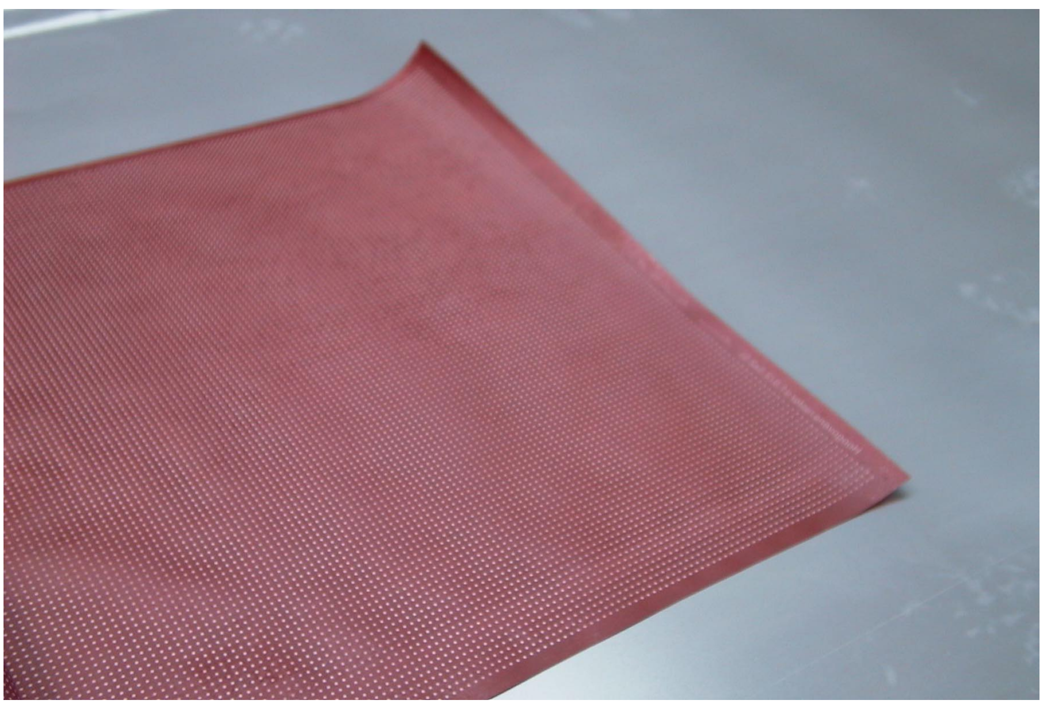


Figure 8.4.1-1 Circle grid pattern

Circle grid analysis was done using the Phast system which can meaure millions of surface points simultaneously.

As a result of the stamping process, the distance between the points changes (figure 8.4-2). The Phast system can measure millions of surface points simultaneously, so it processes complete surfaces, instead of "cutting" the surface in little patches, which are afterwards "stitched" back together (figure 8.4-3). The main advantage is that the complete surface is expressed in one coordinate system that guarantees homogeneous results.

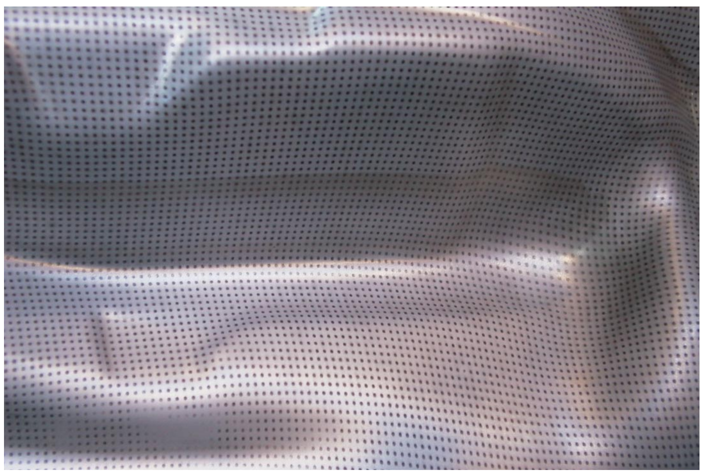


Figure 8.4.1-2 Circle grid pattern on the stamped part

Figure 8.4.1-3 Circle grid strain measurement

Comparison between simulation and manufacturing was done on the hydroformed tubes by defining typical sections and measuring thinning.

The Phast System features fully automatic reconstruction of the camera positions. Thus, images can be taken without prior knowledge of the locations of the camera. This system can detect and correct measurement errors by thorough statistical analysis of the measurement. The large number of images that can be processed, combined with the many surface points that can be measured, provides an outstanding basis for a detailed and fully-documented quality control.

After all, the system enables the user to plot the data measured on the stamped part sections on a Forming Limit Diagram (FLD) and to fit the Forming Limit Curve (FLC) of the material grade and thickness.

8.4.2 Tubular Hydroforming Process

Investigations concerning the applicability of circle grid strain analysis on tubes (tubular hydroforming) leads to the result that it is not common but feasible in principle. One difficulty is that the grid has to be applied on the flat steel sheet prior to the tube manufacturing process. Tubes for the hydroforming process normally were produced on continuous laser or high frequency welding machines where steel strip will be molded continuously into a tube with a longitudinal slot. That makes it difficult to apply the circle grid.

Another difficulty could be damage of the circle grid caused by the tooling in the manufacturing process steps: pre-bending, pre-forming and final hydroforming.

Due to these facts no circle grid strain analysis was performed on the hydroformed tubes in the ULSAC program. Instead, the comparison of the parts manufacturing with forming simulation was performed by first defining typical sections on the hydroformed component, cutting them into the sections and finally measure thinning and thickening.

Circle grids were applied on flat steel sheets prior to stamping the parts because of the expected plastic strains.

8.5 Comparison Forming Simulation with Parts Manufacturing

8.5.1 Stamping

In the stamping process the comparison of the parts manufacturing with forming simulation was performed with circle grid strain analysis.

As a result of the expected plastic strains, different circle grids were applied on flat steel sheets prior to stamping. Circle grids with very small points and small distances in between were applied on flat steel sheets where the forming simulation indicated critical areas of failure. In areas with less expected plastic strains, circles with a diameter of 100mm were applied in the middle area of the flat steel sheet for the Panel Front Door Outer and were measured. The Phast system is not suitable to measure deformation in such a large range.

8.5.1.1 Panel Front Door Outer

The comparison on the Panel Front Door Outer was performed for the material grade BH260. The incremental forming simulation indicated two critical areas of failure. Circle grids with small points were applied on the flat steel sheet BH260 prior to the stamping process. Figure 8.5.1.1-1 shows the comparison of the results on the first identified area.

Comparison between forming simulation and manufacturing of the Panel Front Door Outer shows only marginal differences.

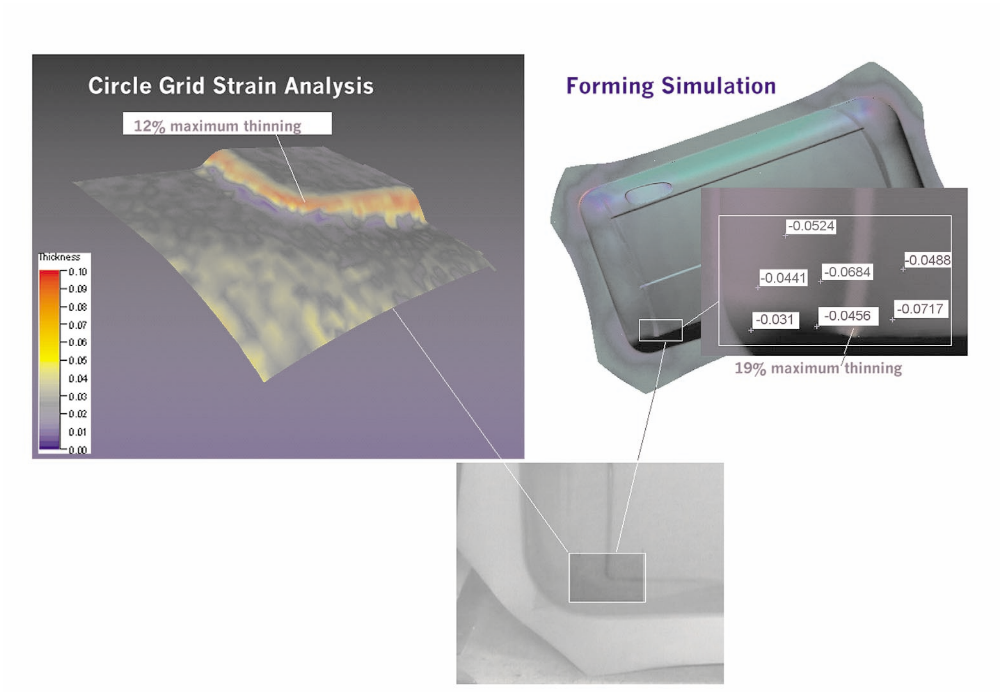


Figure 8.5.1.1-1 Correlation Simulation of Panel Front Door Outer

Figure 8.5.1.1-1 shows the comparison of circle grid strain analysis and incremental forming simulation of the first critical area of failure identified with the forming simulation.

The circle grid strain analysis shows thinning in the corner of the part forming shape of about 12%. The corresponding calculated thinning of the forming simulation amounts to 19%.

The second critical area, measured by circle grid strain analysis indicates maximum

The circle grid analysis shows thinning on the corner of the upper feature line of about 22%, the forming simulation calculates 18%.

thinning on the edge of the upper feature line and the edge of part forming shape of about 22%. The incremental forming simulation calculates thinning of 18% in the same place.

Between the door handle position and the edge of the part forming shape the forming simulation indicates thinning of 8 –12%. The circle grid analysis indicates thinning of about 5 – 11%.

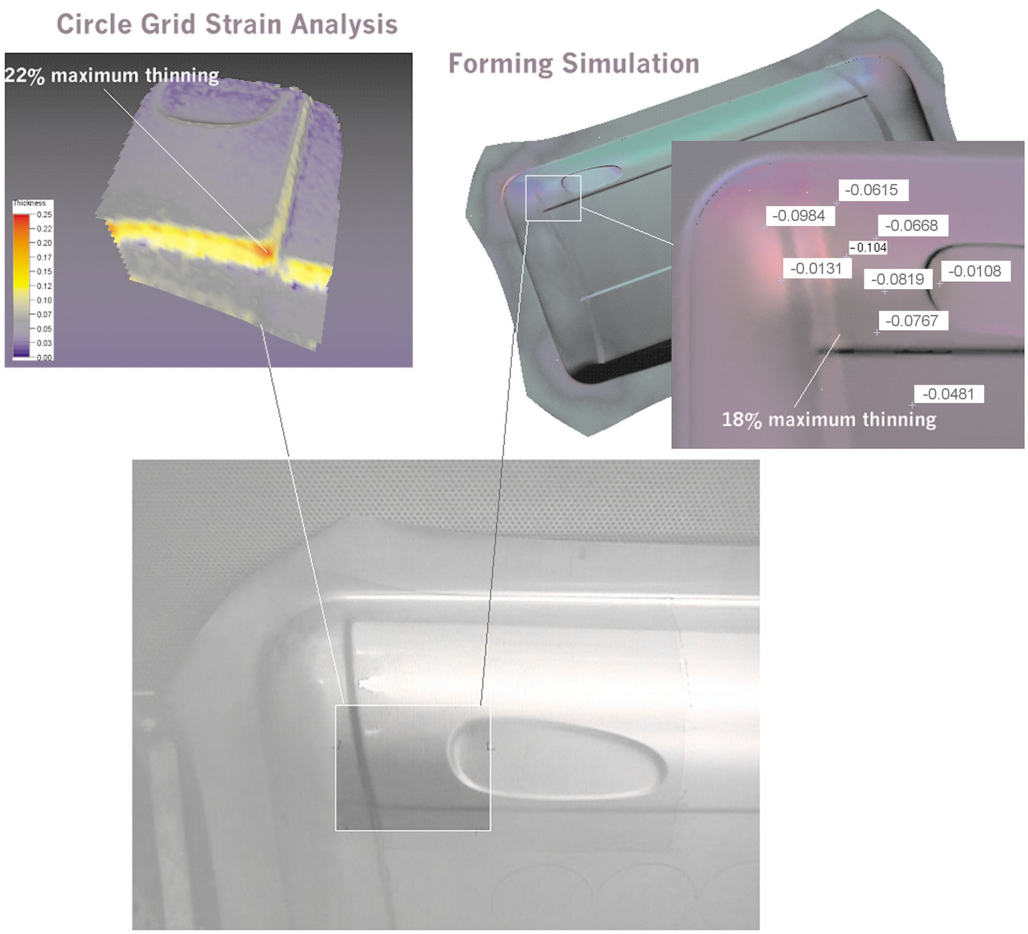


Figure 8.5.1.1-2 Comparison Simulation of Panel Front Door Outer

The comparison of the incremental simulation results and the circle grid strain analyis match quite well in indicated critical areas.

The comparison of the incremental simulation results and the circle grid strain analysis matches quite well in the indicated critical areas and are in a close range of 3-5%. There is no tendency that indicates whether the forming simulation values or the measured circle grid values are generally higher or lower.

The middle area of the Panel Front Door Outer is not critical for failure but the magnitude of deformation could influence oil canning and dent testing results. For this reason the comparison with the forming simulation was performed. Measuring the change of the diameter in major and minor axis after stamping was manually measured.

In the stamping process the starting circle grid diameter of l_0=100mm increases to l_1=100.7mm in major axis and to l_2=100.5mm in the minor axis. The logarithmic magnitude of deformation in major axis is calculated to be φ_1. The logarithmic magnitude of deformation in minor axis is calculated to be φ_2.

$$\varphi_1 = \ln \frac{l_1}{l_0} \qquad \varphi_2 = \ln \frac{l_2}{l_0}$$

The calculated major strain φ_1 amounts to 0.69% and minor strain φ_2 to 0.49%.
Due to the fact of constant volume during the metal forming process:

$$\varphi_1 + \varphi_2 + \varphi_3 = 0$$

and the formula for plastic strain of von Mises φ_v

$$\varphi_v = \sqrt{\frac{2}{3} \bullet ({\varphi_1}^2 + {\varphi_2}^2 + {\varphi_3}^2)}$$

the plastic strain calculates to about 1.2%. The incremental forming simulation calculates a plastic strain of 1.3%, which matches the measurement with circle grids.

In both performed analyses of the Front Door Inner Rear, material thinning occurred along the contour of the radius near the top.

8.5.1.2 Panel Front Door Inner Rear

The comparison of the measured material thinning using circle grids and material thinning calculated in the forming simulation is shown in figure 8.5.1.2-1. In both cases maximum material thinning occurred along the contour of the radius near the top of the Panel Front Door Inner Rear. The circle grid strain analysis measured thinning of 35% while the forming simulation calculated thinning of 28%. The difference in the thinning numbers may be a result of the analytical models for the stamping simulations, based on production-intent tooling.

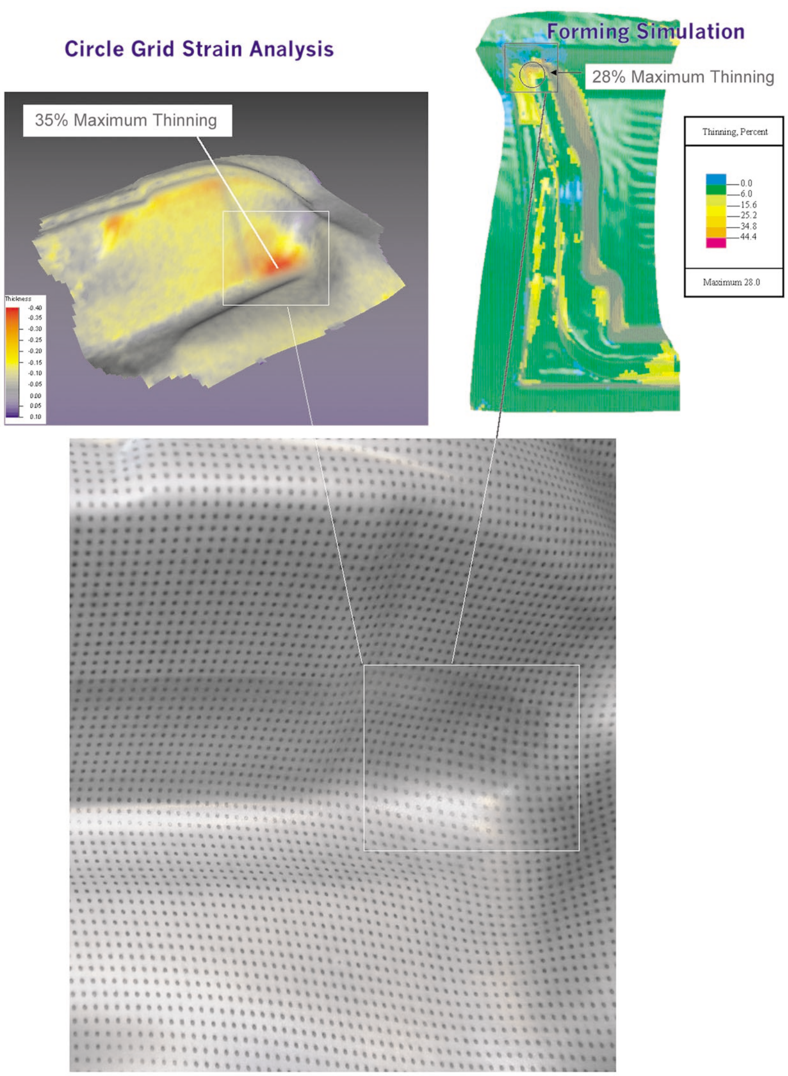


Figure 8.5.1.2-1 Comparison Simulation/Manufacturing Panel Front Door Inner Rear

Both forming simulation and circle grid strain analysis predicted that the upper half of the TWB was a more critical area.

8.5.1.3 Panel Front Door Inner Front

Figure 8.5.1.3 shows the comparison of the circle grid strain analysis and the incremental forming simulation in the upper half of the tailor welded blank which has an initial material thickness of 0.1 mm and therefore was considered a more critical area of the TWB. The circle grid strain analysis shows material thinning of approximately 24-26% on the contour of the radius. The incremental forming simulation calculated material thinning of 22% in the same area. The thinning results of both the circle grid strain analysis and the incremental forming simulation match quite well.

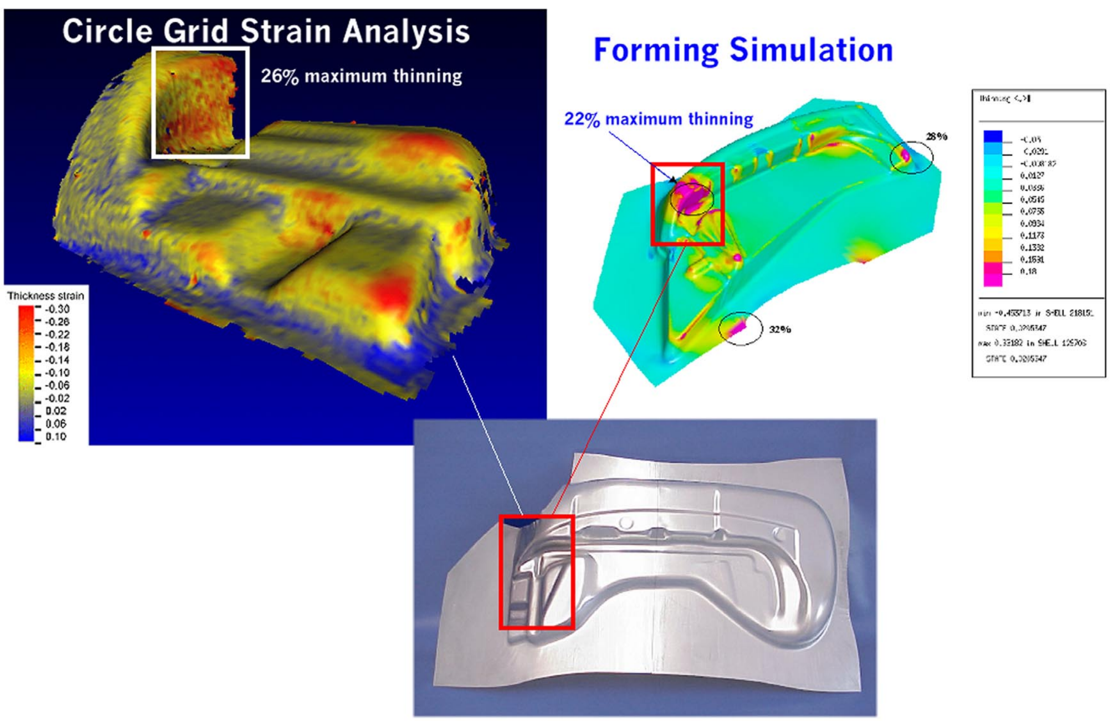


Figure 8.5.1.3-1 Comparison Simulation/Manufacturing Panel Front Door Inner Front

Material thinning on the Panel Mirror Flag Outer occured in both analyses along the contour of the radius at the deepes point of draw.

8.5.1.4 Panel Mirror Flag

The comparison of the measured material thinning by circle grids with the calculated material thinning by forming simulation is shown in Figure 8.5.1.4-1. In both performed analyses material thinning occurred along the contour of the radius at the deepest point of draw. The circle grid strain analysis measured thinning of 28% while the forming simulation calculated thinning of 22%. The difference in the numbers is 5% which could be a result of the analytical model for the stamping simulation that was based on production-intent tooling.

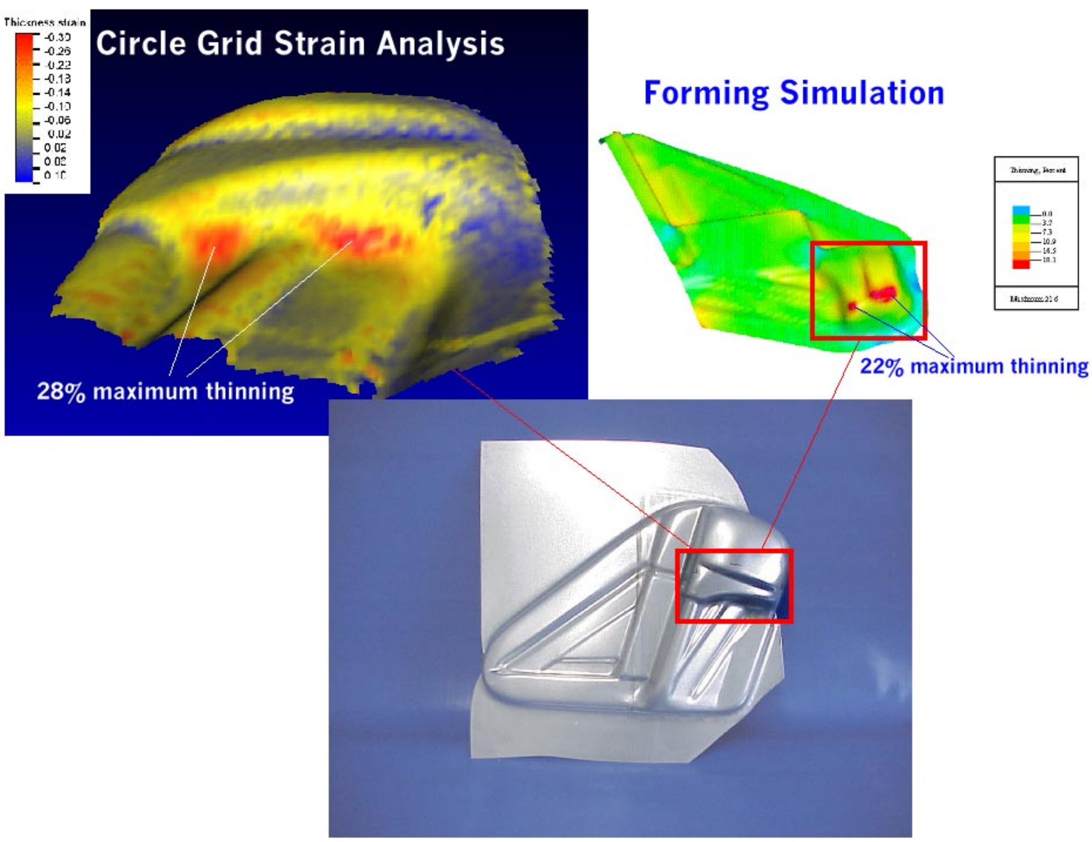


Figure 8.5.1.4-1 Comparison Simulation/Manufacturing Panel Mirror Flag

For the hydroforming tubes, typical sections were sliced and measured into thinning and thickening after the hydroforming process.

8.5.2 Tubular Hydroforming

The comparison of parts manufacturing and the forming simulations was performed by defining typical sections on the hydroformed components, which were cut and measured for material thinning and thickening. The tubular hydroforming process used axial feeding on both ends of the pre-formed tube. Axial feeding was considered in the one-step forming simulation, while no axial feeding was considered in the incremental forming simulation.

8.5.2.1 Hinge Tube

The typical sections that are measured for material thinning and -thickening and the corresponding numbers are shown in figure 8.5.2.1-1. The initial wall thickness of the ULSAC Hinge Tube was 1.2mm. Numbers identified on the hinge tube are section locations whereas, numbers identified on the section example are measuring points. Measurement point three (3) is located on the inner curve and seven (7) is on the outer curve.

	Measurement Point Thickness (mm)							
Section	1	2	3	4	5	6	7	8
0	1.15	1.15	1.20	1.15	1.15	1.15	1.15	1.15
1	1.15	1.25	1.30	1.20	1.10	1.00	0.85	1.00
2	1.10	1.25	1.35	1.25	1.15	1.00	0.90	1.00
3	1.15	1.10	1.15	1.10	1.15	1.10	1.15	1.10
4	1.15	1.10	1.15	1.10	1.15	1.15	1.15	1.15
5	1.15	1.15	1.20	1.20	1.15	1.10	1.15	1.10

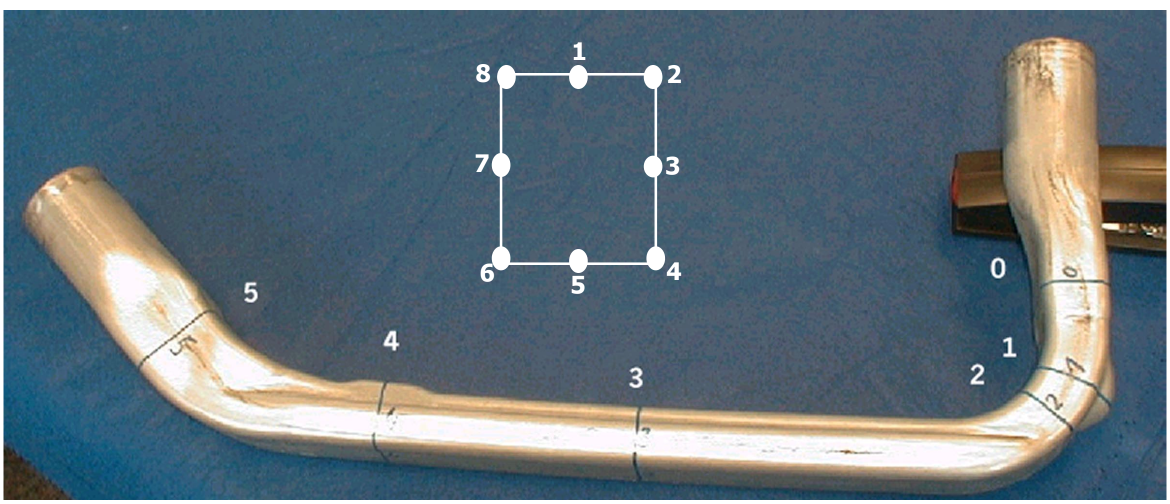


Figure 8.5.2.1-1 Typical measured sections of the Hinge Tube

First try outs done without axial feeding lead to failure which corresponds to the forming simulation.

First try outs without axial feeding lead to failure in section 1, measurement point 7, which correspond with the incremental forming simulation indicating thinning of 34% (figure 8.5.2.1-2)

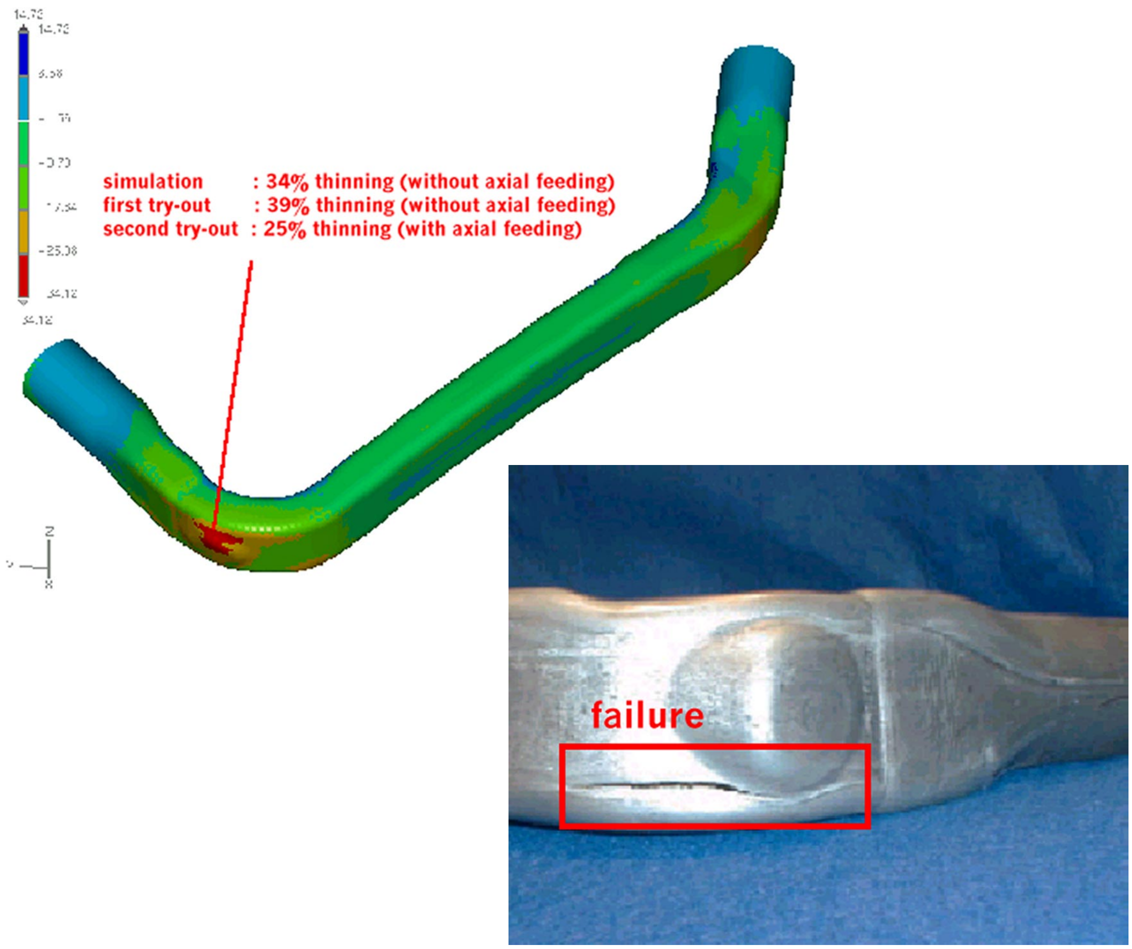


Figure 8.5.2.1-2 Comparison Simulation/Manufacturing Hinge Tube Section 1

Due to axial feeding on the ends of the tube in final parts manufacturing, wall thinning could be reduced from 34% to 25%.

With axial feeding on the ends of the tube, wall thinning in this area was reduced to 25%, which made the parts feasible to manufacture. The material thickening of the measured Hinge Tube (section 1, measurement point 3) amounts to 10%. The incremental forming simulation calculated thickening of 13% (figure 8.5.2.1-3)

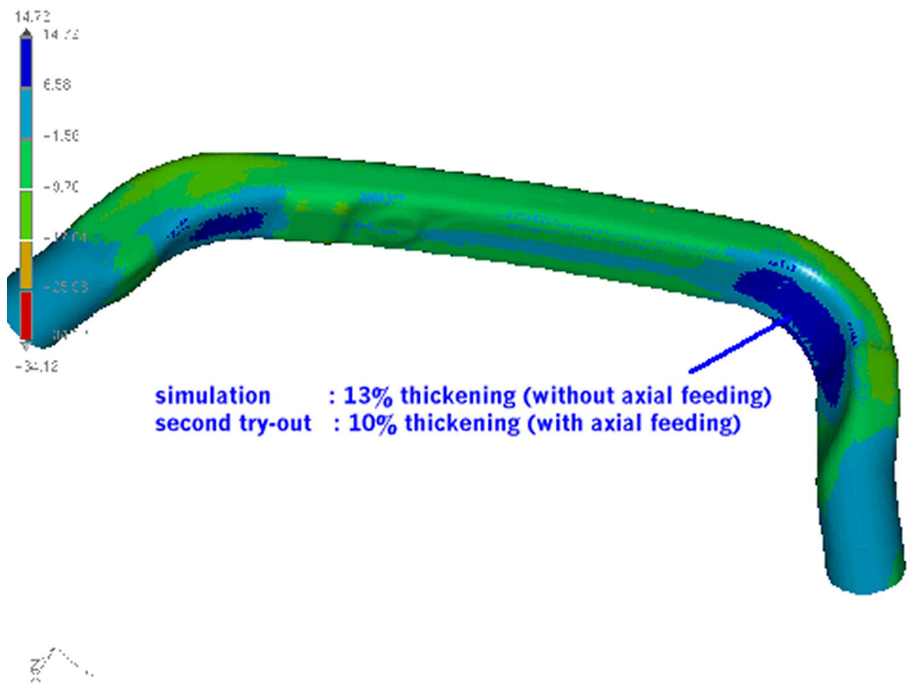


Figure 8.5.2.1-3 Comparison Simulation/Manufacturing Hinge Tube Section 1

The one-step forming simulation nearly match the circle grid analyses in the outer 90-degree bending radius and the inner bending radius.

Also in section 1 the one-step forming simulation (see Figure 8.5.2.1-4) indicated material thinning on the outer 90-degree bending radius of 20% and material thickening on the inner bending radius of 9%. These calculations match the measured results and the incremental simulation results.

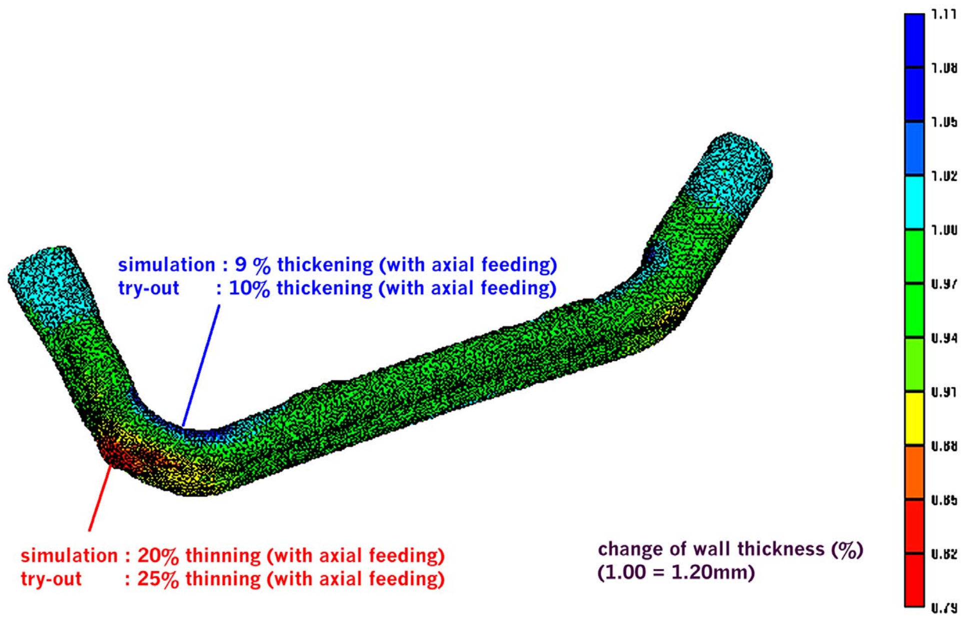


Figure 8.5.2.1-4 Comparison Simulation/Manufacturing Hinge Tube Section 1

An overall thinning of 3-5% was measured on the Latch Tube, which closely matches the forming simulation.

The measurements in section 3 and 4 indicated a overall thinning of 3-5% as a result of the final hydroforming calibration process. These measurements closely match the incremental forming simulation and the one-step simulation (figure 8.5.2.1-5).

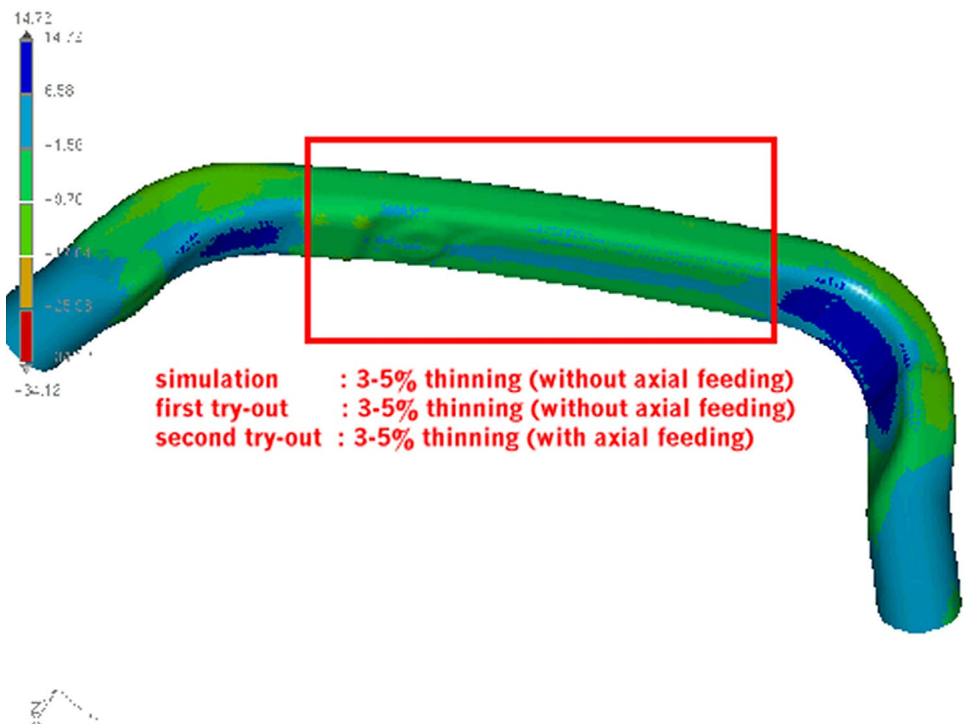


Figure 8.5.2.1-5 Comparison Simulation/Manufacturing Hinge Tube Section 3 and 4

Axial feeding was also able to reduce the wall thinning on the Latch Tube in final parts manufacturing.

The measured material thinning with axial feeding in section 5 (measurement points 6 and 8) was 9%. Figure 8.5.2.1-6 shows the incremental forming simulation without axial feeding calculated material thinning of 20%. First try out without axial feeding led to material thinning of 22%. The one-step simulation in Figure 8.5.2.1-4 calculated thinning of approximately 11%.

The incremental forming simulation without axial feeding corresponds well to the the first try out without axial feeding. In the one-step simulation, axial feeding is considered and the result match the tryout with axial feeding. The positive effect of axial feeding results in an actual reduced material thinning as predicted in the one-step simulation and validated with the part measurements.

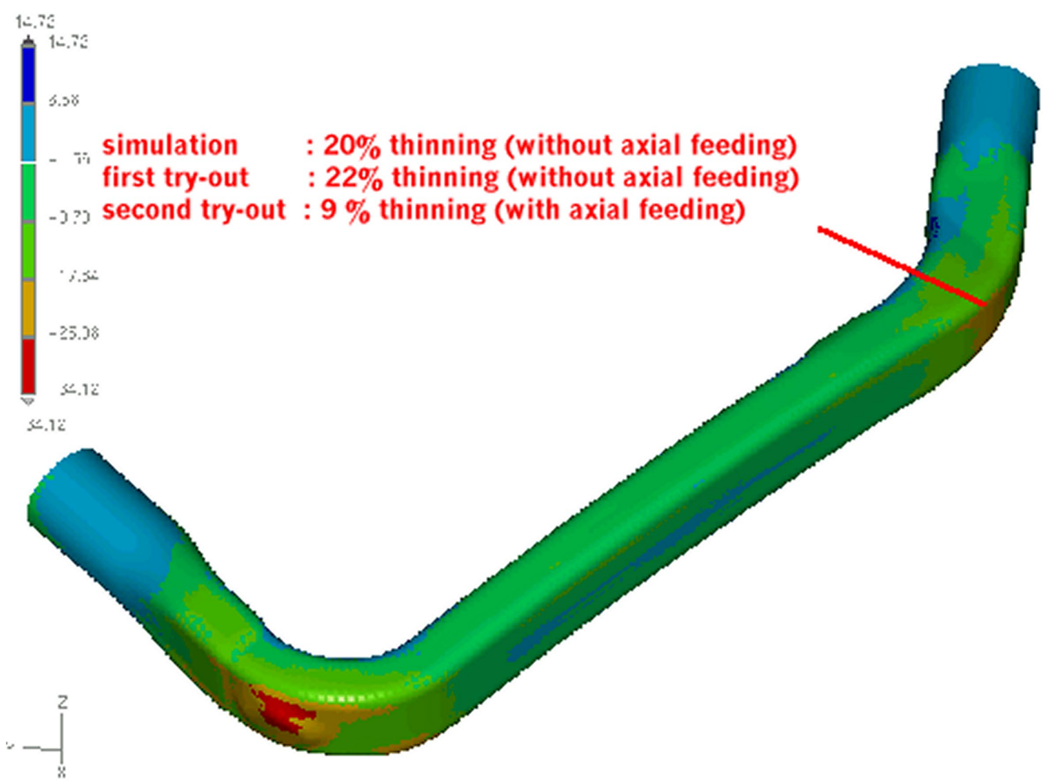


Figure 8.5.2.1-6 Comparison Incremental Simulation/Manufacturing Hinge Tube Section 5

For the hydroforming tubes, typical sections were sliced and measured into thinning and thickening after the hydroforming process.

8.5.2.2 Latch Tube

The typical sections measured for material thinning and -thickening and the corresponding numbers are shown in two different views in figure 8.5.2.2-1 and figure 8.5.2.2-2. The initial wall thickness of the ULSAC Latch Tube was 1.0mm. Numbers identified on the latch tube are sections whereas, numbers identified on the section example are measuring points. Measurement point three (3) is located on the inner curve and seven (7) is on the outer curve.

	Measurement Point Thickness (mm)							
Section	1	2	3	4	5	6	7	8
0	0.90	0.90	1.10	0.90	0.95	0.90	0.90	0.85
1	0.90	1.00	1.10	1.00	1.00	0.90	0.80	0.90
2	0.90	1.00	1.15	1.00	0.90	0.85	0.80	0.85
3	0.85	0.85	0.90	0.80	0.70	0.80	0.90	0.90
4	0.80	0.70	0.85	0.95	1.00	1.00	0.95	0.85
5	1.00	1.00	0.90	0.80	0.80	0.80	0.90	1.00
6	0.90	0.85	0.80	0.90	1.00	0.95	0.90	0.85
7	0.85	0.90	0.95	0.90	0.90	0.95	0.90	0.85
8	0.90	0.90	0.95	0.90	0.95	0.90	0.95	0.90

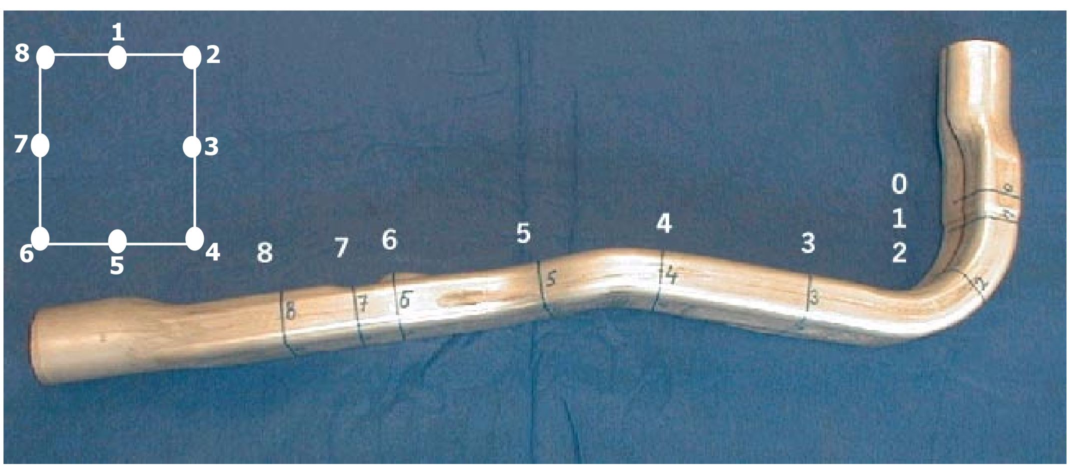
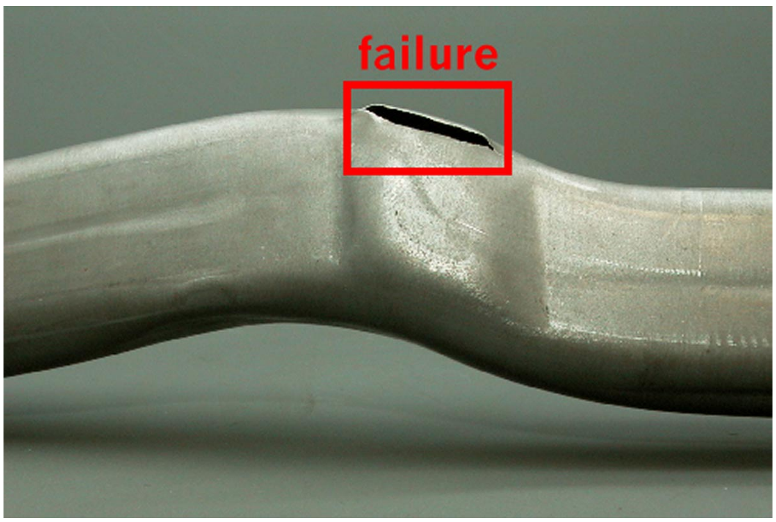


Figure 8.5.2.2-1 & 8.5.2.2-2 Typical measured sections of the Latch Tube

During the first try outs, the Latch Tube failed, which you can also see in forming simulation, and small design changes were necessary.

First try outs were performed without axial feeding. Figure 8.5.2.2-3 shows the comparison of the first tryout with the incremental forming simulation. The forming simulation that calculates thinning of 38% matches the first try out without axial feeding (37% thinning) well. As a result of this material thinning the component failed in the manufacturing process. Even axial feeding could not influence the forming limit in this middle area of the component. Therefore, small design changes were done to make the part feasible to manufacture.



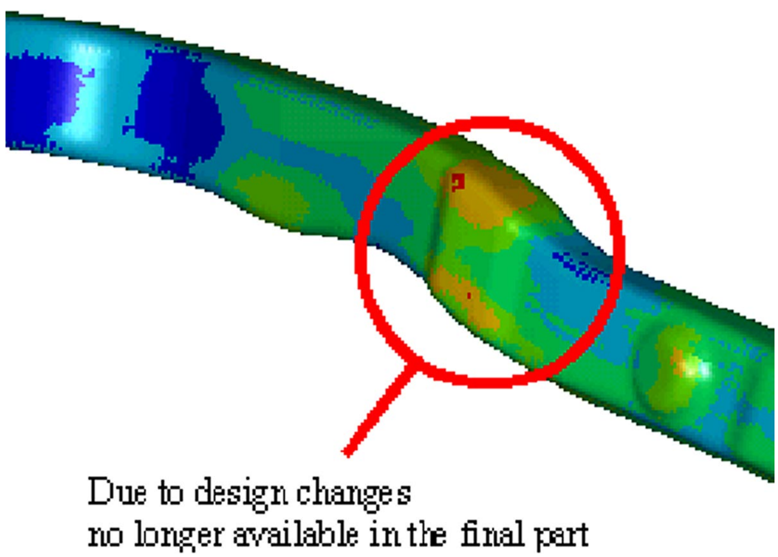


Figure 8.5.2.2-3 Comparison Simulation/Manufacturing Latch Tube

Axial feeding on both ends of the tube reduced material thinning to 20% in this section and made the part feasible to manufacture.

The first try outs without axial feeding the part failed in section 1 (measurement point 8) where material thinning of 35% occurred. The incremental forming simulation indicated thinning of 33%, which matches the try out results. Axial feeding on both ends on the Latch Tube reduced the material thinning in this section to 20% and made the part feasible to manufacture.

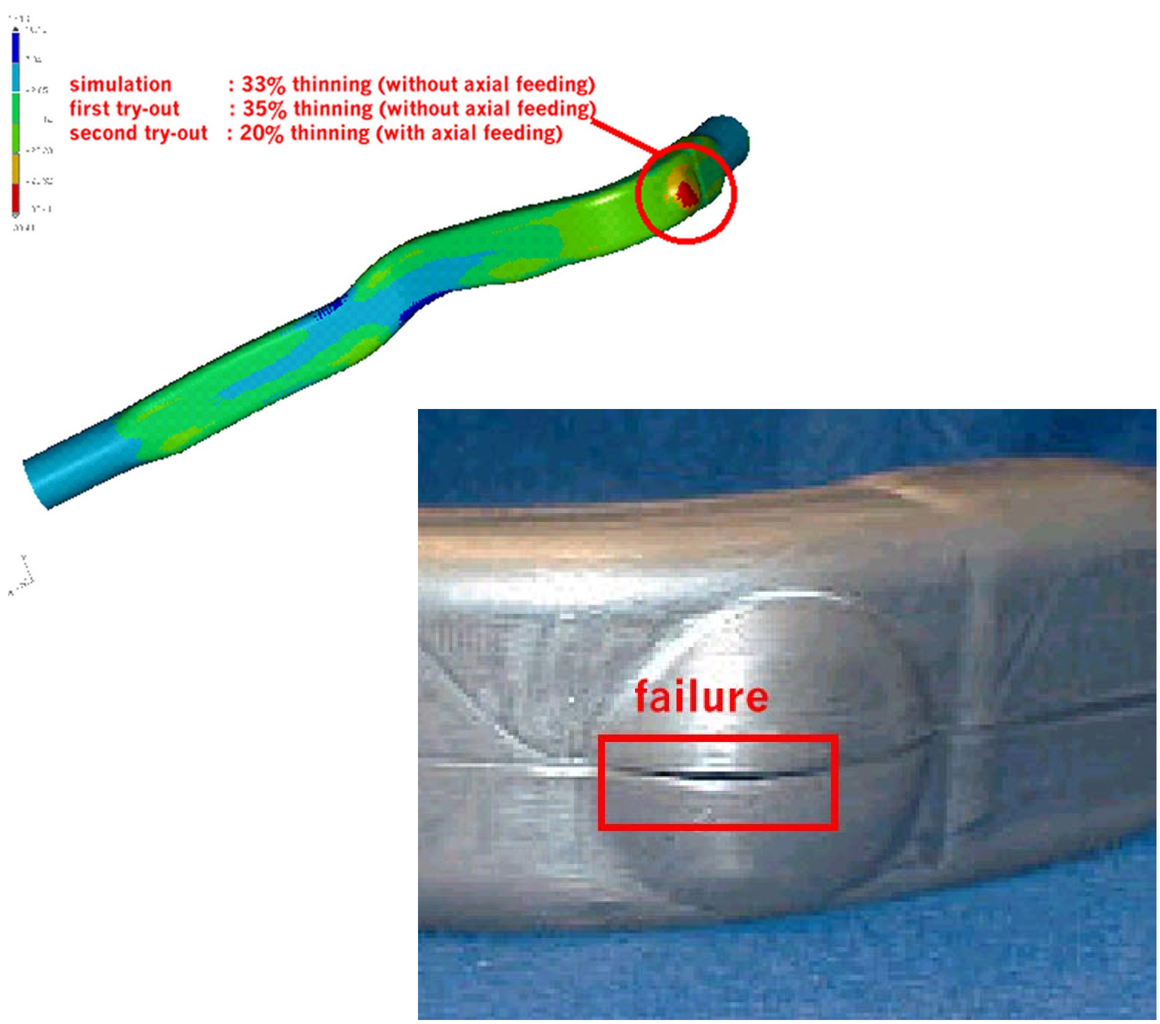
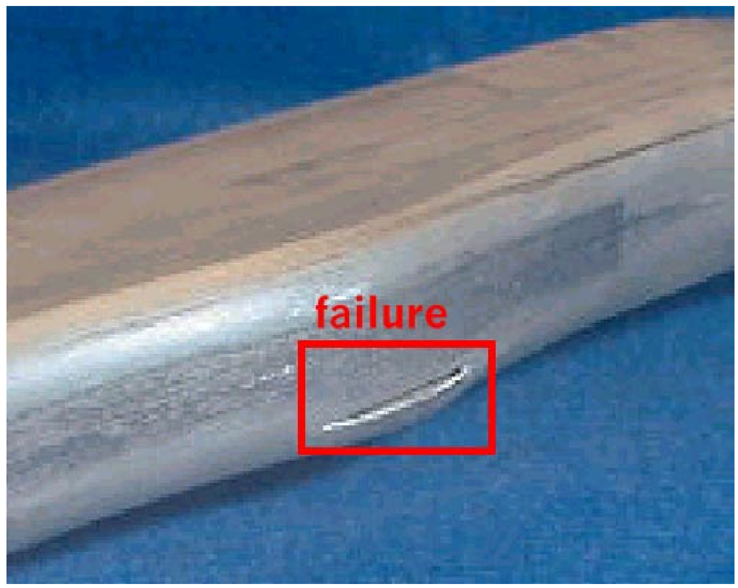


Figure 8.5.2.2-4 Comparison Simulation/Manufacturing Latch Tube Section 1

Small changes in the radius were necessary after first try outs resulted in an area of failure.

Section 3, axial feeding could not improve the forming limit. Because of the bending in front of the predicted failure area, material cannot be fed from the ends of the tube to this area. As a result of this, measurement point 5 indicates material thinning of about 30%. The incremental forming simulation showed material thinning of 27%. Small changes in the radius after first try outs failures were made (Figure 8.5.2.2-5) and the sufficient elongation of the used material made the part feasible to manufacture.



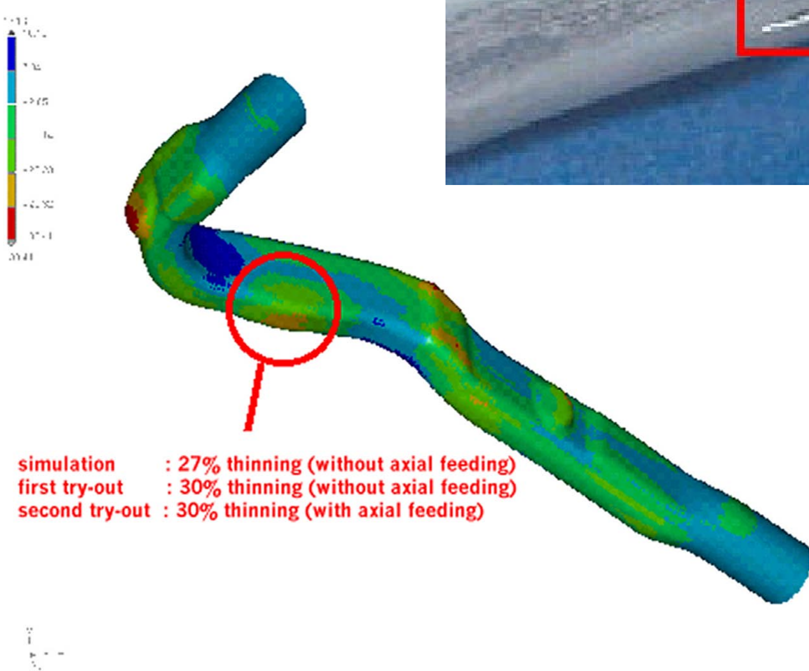


Figure 8.5.2.2-5 Comparison Simulation/Manufacturing Latch Tube Section 3

The forming simulation matched the results of the manufactured part in an area where axial feeding could not influence the forming limit.

Local thinning in section 6 caused material thinning of 20%. The results of the incremental forming simulation indicated thinning of 21.5% which corresponds to the try out (figure 8.5.2.2-6). Though the simulation was done without axial feeding, the result matches the try out. Axial feeding could not influence the forming limit in this area because of the distance of the location from the end of the tube.

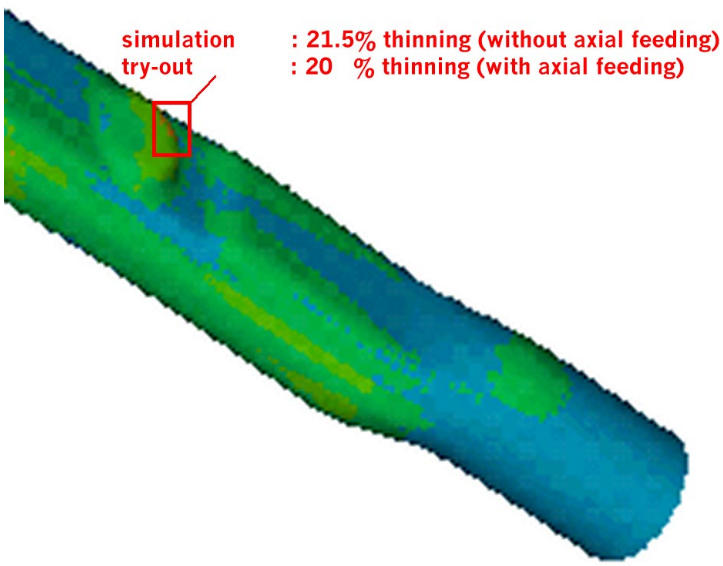


Figure 8.5.2.2-6 Comparison Simulation/Manufacturing Latch Tube Section 6

One-step simulation could not assess sections where the tool geomety influences the material thinning.

The comparison of the one-step forming simulation with the hydroformed Latch Tube is shown in figure 8.5.2.2-7. Material thinning on the outer 90-degree bending radius (section 1) was calculated to 23%. On the hydroformed part thinning of 20% was measured at the same location. On the inner bending radius of this section 8% material thickening was calculated by the one-step forming simulation, while the measured material thickening was 10%.

First try outs were made without axial feeding. Figure 8.5.2.2-7 shows the correlation of try out with the one-step forming simulation in a section that is no longer available in the final part design. The design was later changed as a result of the forming simulation. Thinning of 20 % was calculated in the one-step forming simulation, which does not correspond with the tryout with axial feeding, where a thinning of 37% occurs. The missing tool geometry and therefore the missing friction could lead to this result. Considering the missing tool geometry the tool geometry of the one-step simulation are sufficient to get a very early information of supposed areas of failure.

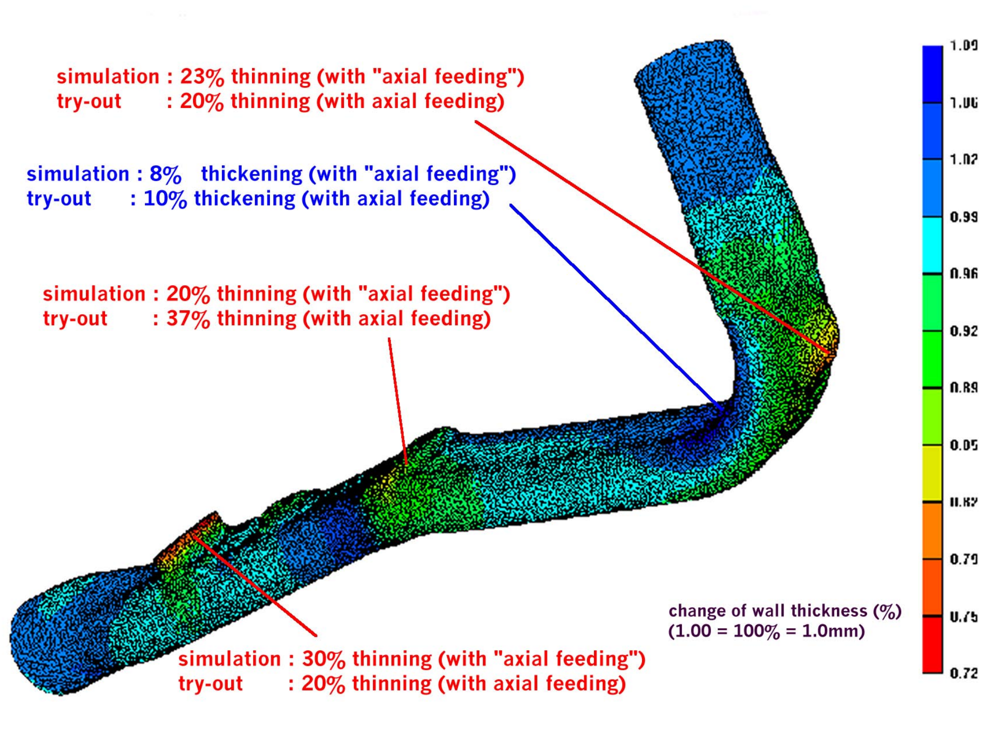


Figure 8.5.2.2-7 Comparison Simulation/Manufacturing Latch Tube

9 DH Build

Porsche's Research & Design facility in Weissach, Germany was chosen for the assembly of the DHs.

Background

With the completion of the ULSAC Concept Phase, the ULSAC Consortium decided to validate one of the concepts in the Validation Phase. This decision involved proceeding from a conceptual study into the DH build of the ULSAC frameless door concept and the predicted mass savings and structural performance could be validated.

Porsche's Research and Design facility in Weissach, Germany was chosen for the assembly of the prototype doors. With the latest welding and assembly tools, alongside Porsche's qualified team of engineers and other specialists, the ULSAC door became a reality.

9.1 Joining Technologies

9.1.1 Laser Welding

The use of laser technology in the automotive industry has been increasing for many years. Today the number of applications has increased due to laser welding and similar adaptations such as laser brazing being considered state-of-the-art. The major reasons include the predominately high static and dynamic strength of the joints, single-side weld access, small thermal impact zone and weight savings by designing for laser welding.

State-of-the-art laser technology was used on the joints of the ULSAC door. The ROFIN SINAR laser is a diode pumped solid state laser, and is capable of welding and cutting. In contrast to the older lasers where a lamp pumped the Nd-YAG-crystals, new lasers use small laser diodes which are merged into bigger stacks. This technology uses less energy leads to increased power efficiency and an optimized beam quality.

The new Rofin Sinar diode pumped solid state laser was used for laser weld seams on the ULSAC DH door structure.

The ROFIN SINAR laser used for the ULSAC DH door structure assembly produces an output of 3000 Watt. The beam is transported to the robot head through a glass fiber cable (10m) and connected with the laser welding head.

Figure 9.1.1-1 New diode pumped solid state laser of Rofin Sinar

The following seams (see Figure 9.1.1-2) were created with the laser. Additional the welding of the bushings (Hinge- and Latch Bushings) was done by a combination of laser welding (head of the bushings) and metal arc welding on the opposite side (see Figure 9.1.1-3)

No. 1 Front Door Hinge Bushing to Front Door Hinge Tube
No. 2 Front Door Latch Bushing to Front Door Latch Tube
No. 3 Reinforcement Latch to Front Door Latch Tube
No. 4 Front Door Inner Front to Front Door Hinge Tube
No. 5 Front Door Inner Rear to Front Door Latch Tube
No. 6 Mriror Flag Outer to Front Door Outer Belt Reinforcement

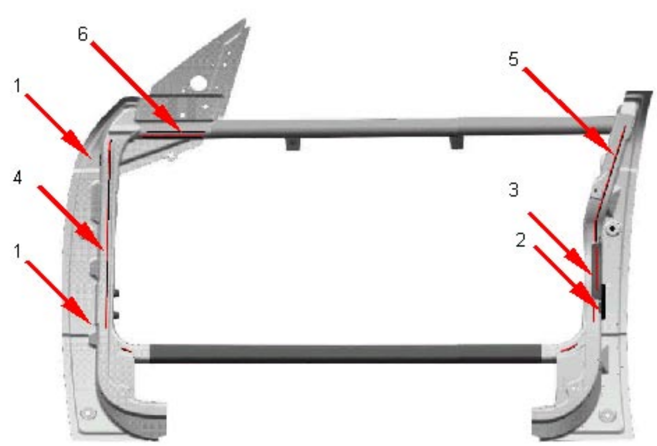


Figure 9.1.1-2 Overview of the several laser weld seams on the ULSAC door

The welding of the bushings was done by a combination of laser welding and metal arc welding.

Mirror Flag Outer to Front Door Outer Belt Reinforcement (#6)

Front Door Inner Rear to Front Door Latch Tube (#5)

Front Door Inner Front to Front Door Hinge Tube (#4)

Reinforcement Latch to Front Door Latch Tube (#3)

Front Door Hinge Bushing to Front Door Hinge Tube (#1)

Front Door Latch Bushing to Front Door Latch Tube (#2)

Figure 9.1.1-3 Detail of several laser weld seams on the ULSAC DH

Resistance spot welding was another important joining technique used for assembly of the ULSAC DH door structure.

9.1.2 Resistance Spot Welding

Resistance spot welding is today's most common joining technique used by automotive manufacturers. This technology is well known throughout the industry due to its reliable, affordable joining of steel auto bodies and double-sided zinc coated sheets. The prototype manufacturing at the R&D Center in Weissach uses Matuschek™ device controls and a welding gun from Duering™.

The Matuschek™ control works at medium frequencies (1000Hz) and uses a calibration-step to react to these influences. During the calibration the current is kept constant. Together with a suitable choice of welding current/voltage, gun force and time, a good weld point is achieved. After the first weld point is identified, the calibration data can be recalled from a connected computer to produce further weld points. In contrast to a thyristor controlled device with a reaction time of 10ms, the inverter system is much faster with a reaction time of 1ms. Therefore, it is possible for the device to react to the following influences:

- voltage fluctuations
- shunts
- electrode wear
- electrode force fluctuations
- small edge distances

These influences are eliminated by changing the welding current or time. Welding splashes are monitored by the system and shown by an error message or an optional shutdown of the current. The process of adaptation to each weld point guarantees a good weld joint.

Spot welds were used to join the Panel Mirror Flag Outer to the Panel Front Door Inner Front.

Figure 9.1.2-1 Duering™ weld device with Matuschek™ control system

The spot weldings on the ULSAC door are used to join the mirror flag outer to the front door inner front. Spot welds are also used to join the Panel Door Outer with the Panel Front Door Front and Rear on the lower inside overlap.

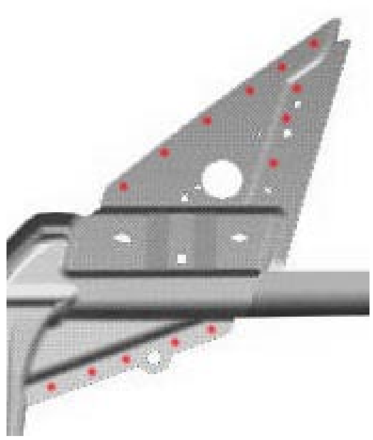


Fig 9.1.2-2 Resistance Spot Welding of the Mirror Flag Outer to Front Door Inner Front

Generally, metal arc welding is used to join parts which are only accessible from one side, or in areas with strong structural strain.

9.1.3 Metal Arc Welding

It is also common for automotive manufacturers to use metal arc welding. Generally, metal arc welding is used to join parts which are only accessible from one side, or in areas with strong structural strain. The metal arc welding uses thermal energy of an arc, which burns between an electrode and the part. To protect the melting against uncontrolled oxidation and other reactions, a gas mixture is used. Together with a suitable electrode material, which is transferred to the welding seam, it is possible to join parts with good mechanical properties.

The front door frame (hinge tube, latch tube, lower tube and outer belt reinforcement), bushings and the regulator attachments were all joined using metal arc welding.

The first assembly step of the ULSAC DH door structure used metal arc welding to assemble the front door frame .

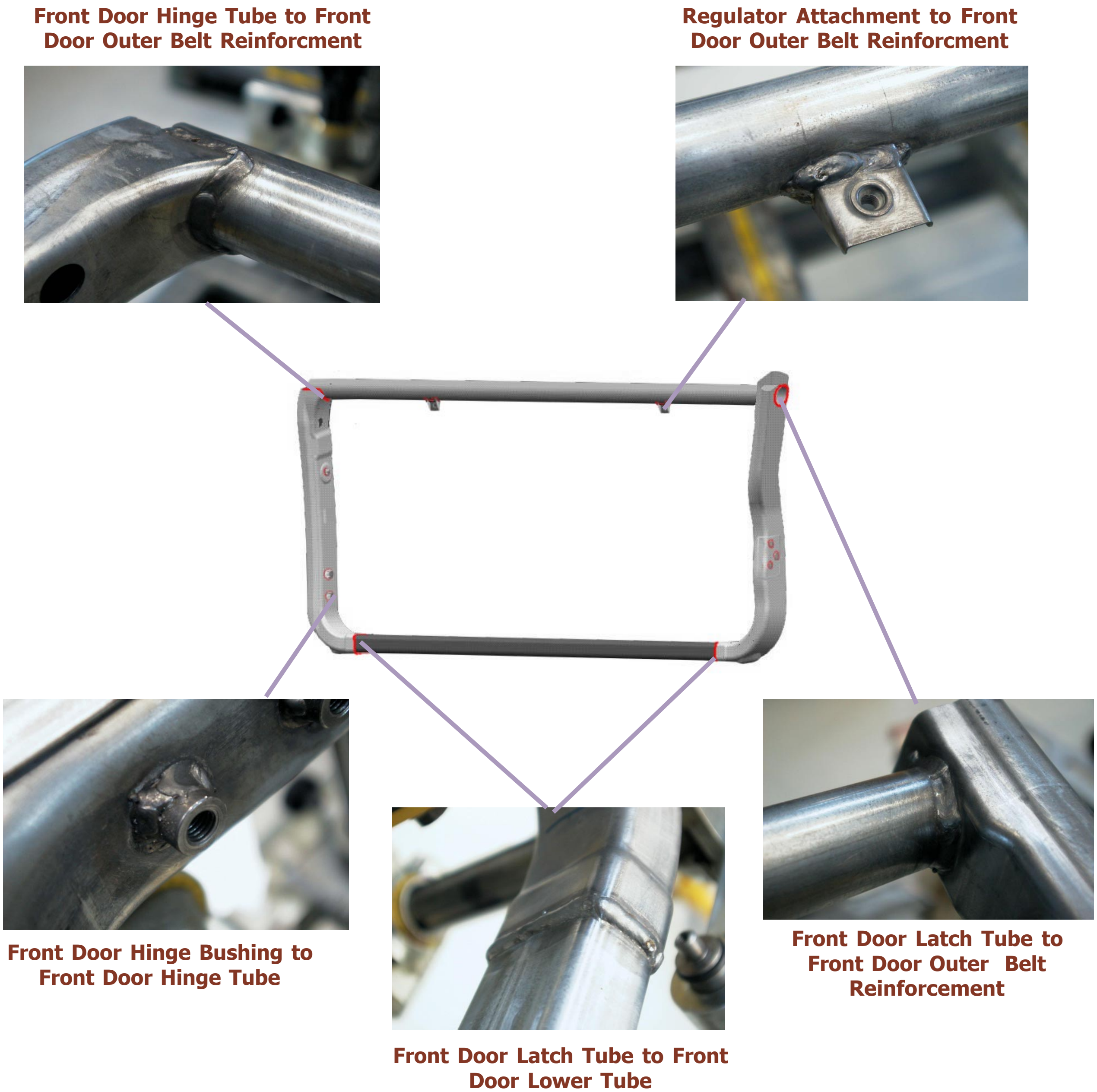


Figure 9.1.3-1 Detail of several metal arc welding joints

The ULSAC DH door structure is bonded in the hem flanges and between the lower tube and Panel Front Door Outer.

9.1.4 Adhesive Bonding

Bonding is a simple, reliable joining method. The benefits of bonding include ease of application, increased stiffness, good damping behavior (acoustics), corrosion protection of narrow flanges and the possibility to connect different types of materials. The most important application is the bonding of hem flanges and structural reinforcements in car doors, hood and decklids.

The ULSAC DH door structure is bonded in the hem flanges and between the lower tube and the Panel Front Door Outer. For the hem flanges, an epoxy-bonding agent was used. This epoxy bonding agent (BETAMATE 1493 from Gurrit Essex) is a one-component reactive bonding agent which hardens at a temperature of 170°C. It can be applied on all steels used in the automobile industry and protects the joined parts from corrosion. Oiled parts are suitable, too much oil must be removed. Bonding also has good resistance against several other chemicals.

Adhesive	Quality	Comments
Basic	Epoxy resin	
Color	Blue	
Density (23 C)	1.12 g/ml	at 23 C
Volatile components	< 1%	
Viscosity	4·000 Pas (23 C, 1s^{-1})	at 23 C, 1s^{-1}
Fire point	> 150 C	
Hardening	180 C / 30 min	
Yield Strength	40.0 MPa	DIN 53 504
Elongation after fracture	14.70%	DIN 53 504
Elastic Module	1800 MPa	DIN 53 504
Combined tension and shear resistance (.75 mm / 1.5 mm)	18.7 Mpa 29.2 Mpa	EN 1465

Figure 9.1.4-1 Technical data of BETAMATE 1493

Two bonding agents, BETAMATE 1493 and Terostat 3211, were used for the ULSAC DH door structure.

The other bonding agent (Terostat™ 3211) is a sealing material from Teroson™ , which vulcanizes and expands under heat influence. It is a self-sealing, plastic adhesive tape based on caoutchouc, which also sticks on oily surfaces. After heat treatment the adhesive tape expands, vulcanizes and builds up a foam-like structure which improves the acoustic damping behavior of the door and stabilizes the outer panel.

Feature	Quality	Comments
Basic	Caoutchouc resin	
Color	Black	
Density	1.15 g/cm‡	at 20 C
Dry content	0.99	
Penetration	46 1/10 mm	cone 150g, 6s, 20 C
Expansion	60-90%	
Flow behavior	No flow off	
Corrosion resistance	Good	168 h to DIN 50021
Combined tension & shear resistance	0.2 Mpa	2 mm thickness
Temperature	- 40 to 100 C	for short times up to 200 C

Figure 9.1.4-2 Technical Data for Terostat 3211 sealing material

Figure 9.1.4-3 Terostat 3211™ sealing material between the Front Door Lower Tube and the Front Door Outer

The complete fixture system as it was planned for actual assembly was designed using CATIA.

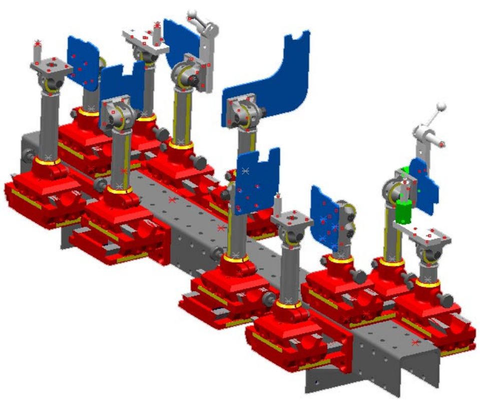
9.2 CAD

The complete assembly was developed with a CAD system (CATIA™) in which the different parts can be adapted to a virtual fixture system. Therefore, it was possible to design the complete fixture system as it was planned for actual assembly. In contrast to actual production, the number of assembly fixtures is reduced because several assembly steps can be done in one fixture.

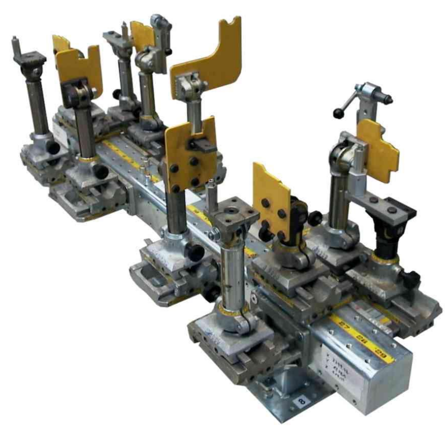
In the case of the ULSAC doors, two fixture were needed:

- Assembly Front Door Frame
- Assembly Front Door Frame with Sheet Parts

An example of the CATIA fixture design and actual fixtures is shown in Figure 9.2-1.



CATIA Fixtures



Actual Fixtures

Figure 9.2-1 Assembly Fixtures (CAD and Actual)

Assembly of the ULSAC DH door structure was divided into three steps - done by both Porsche AG and Stickel.

9.3 Assembly

The Assembly of the door structure can be divided into three steps:

- *Subassembly #1:* Joining of tubular parts, Hinge Tube, Latch Tube, Lower Tube and Outer Belt Reinforcement and Hinge Bushings, the Regulator Attachment Brackets and Latch Reinforcement)

- *Subassembly #2*: Joining of Front Door Frame with the Front Door Inner Parts (Front Door Inner Front, Front Door Inner Rear, Mirror Flag Outer and Latch Bushings)

- *Subassembly #3:* Bonding hem flanging and spot welding of Front Door Outer Panel with Subassembly #2

Subassembly #1 and #2 were assembled at Porsche R & D Center in Weissach, Germany. Subassembly #3 was done at Stickel in Loechgau, Germany. As described in the other chapters several joining methods were used in the three assembly steps. The hem flanges were bonded with Betamate 1493.

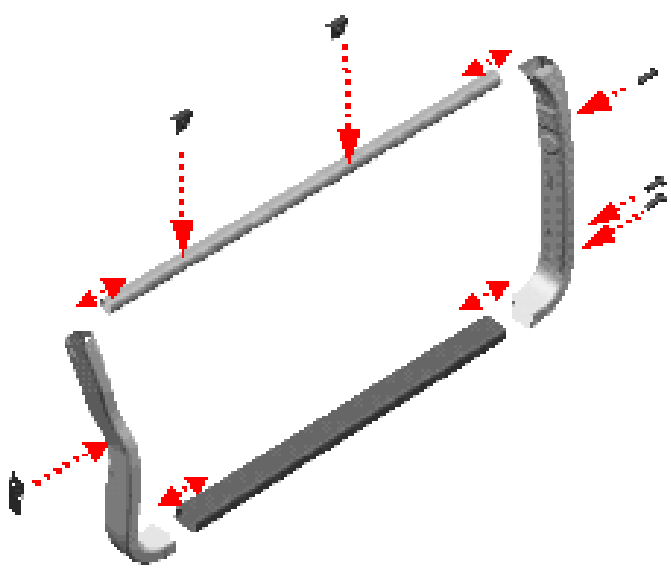


Figure 9.3-1 Subassembly #1 (CATIA): Front Door Frame

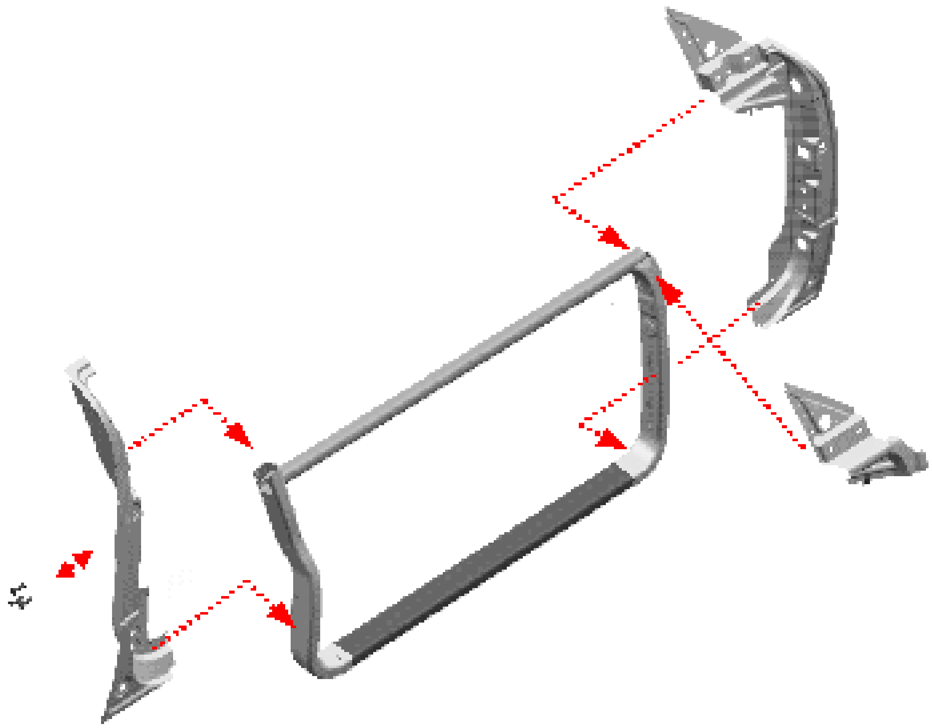


Figure 9.3-2 Subassembly #2 (CATIA): Front Door Inner Parts to Front Door Frame

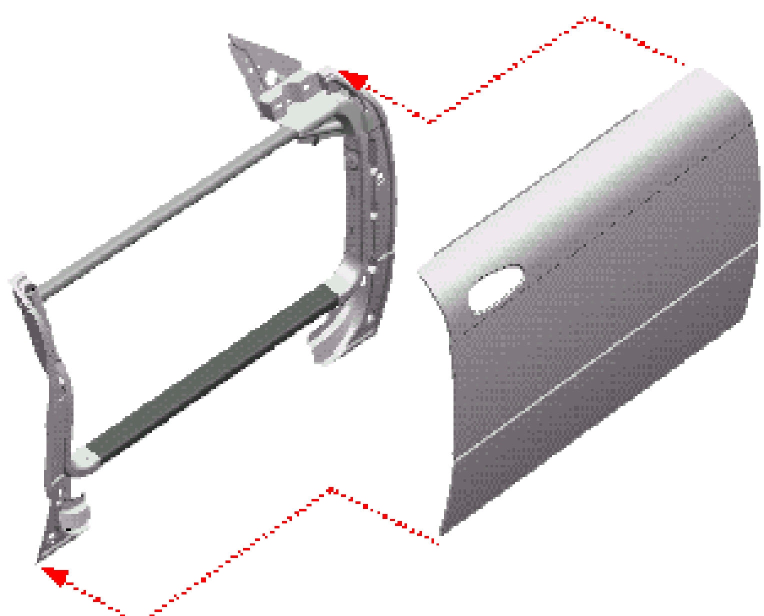


Figure 9.3-3 Subassembly #3 (CATIA): Front Door Outer

Once the front door frame was assembled, the Front Door Inner Parts were attached using welding.

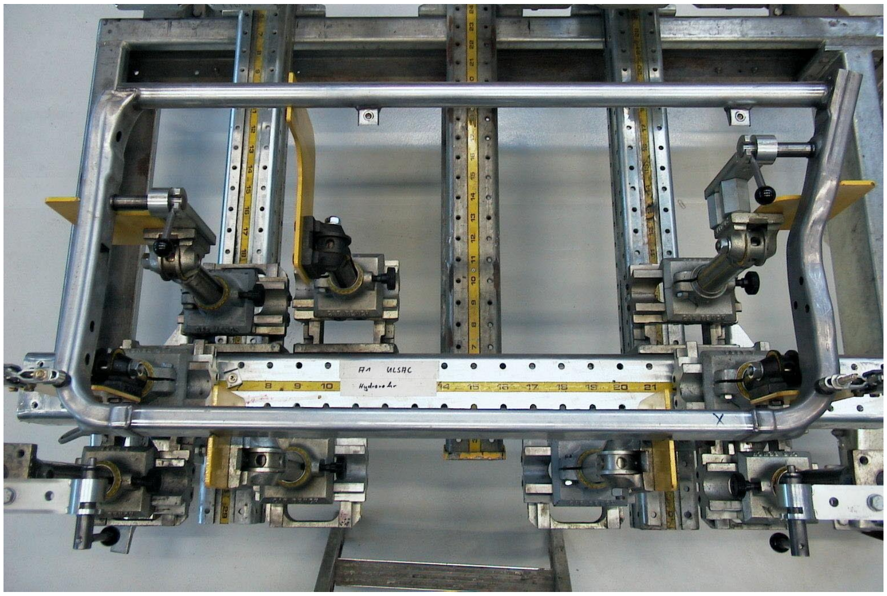


Figure 9.3-4 Subassembly #1: Front Door Frame in Assembly fixture

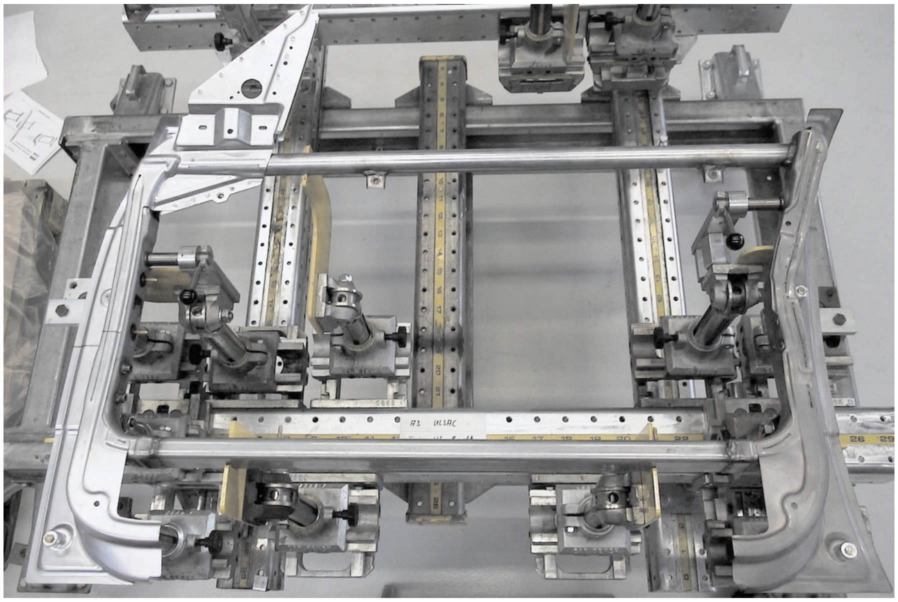


Figure 9.3-5 Subassembly #2: Front Door Inner Parts to Front Door Frame in Assembly fixture

Assembly time and cost were reduced by combining virtual with actual assembly for the assembly and fixture development process.

Figure 9.3-6 Subassembly #3: Bonding and hem flanging of the Front Door Outer

9.4 Conclusion

For the ULSAC DH door structure assembly, assembly time and cost were reduced by combining virtual with actual assembly for the assembly process and fixture development. The realization of the ULSAC-Door was the result of the combined virtual and real assembly at Porsche in Weissach. Changes resulting from virtual assembly tryouts during the ULSAC DH door structure development process could be realized fast in an early stage without any effect on the actual assembly fixtures.

10 Testing and Results

In the ULSAC Validation Phase the DH door structure was tested for structural performance, dent resistance and oil canning

Background

In the ULSAC Validation Phase, testing of the ULSAC door structure was undertaken to validate the design and to select the best suited Door Outer Panel material for the ULSAC DH door structure. Two types of testing were performed:

- Testing for structural performance
- Testing for dent resistance and oil canning

Testing for structural performance was undertaken to confirm that the structural performance is state-of-the-art for today's frameless door.

10.1 Testing for Structural Performances

10.1.1 Benchmarking Testing of Frameless Doors

The ULSAC Concept Phase concentrated on design concepts for all types of automotive closures (doors, decklids, hoods and hatches). The benchmarking undertaken in this phase was based on available data (1996 to 1997). With respect to doors, a mixture of door types without specific focus on frameless doors were benchmarked and this data was used for target setting in the Concept Phase. For the ULSAC Validation Phase the ULSAC Consortium selected the frameless door structure concept for closure validation, to be built and tested as a demonstration example representative of all closure concepts developed in the Concept Phase. To better understand the structural performance of today's frameless state-of-the-art door structures, benchmarking was undertaken in respect to:

- Mass
- Vertical sag stiffness
- Upper and lower lateral stiffness
- Quasi-static side intrusion

The intention was to compare the structural performance test results of the ULSAC DH door structure with the benchmarking results of frameless door structures.

For the frameless door benchmarking, three (3) doors taken from vehicles currently in production and sold worldwide were purchased and tested. The nature of these doors is not identified in this report and they will be referred to as door A, B and C. All door structures were tested on the same testing devices to ensure the compatibility of results.

Benchmarking testing for structural performance was performed on frameless doors in the Validation Phase.

10.1.2 Mass of ULSAC DH Door Structure

The ULSAC DH door structure featuring a 0.7 mm thickness Stamped Panel Front Door Outer was measured at a mass of 10.47 kg. This is 1.76 kg below the target mass of 12.23 kg as specified in the ULSAC Concept Phase.

For the purpose of comparing different doors of different sizes, the mass of each door was normalized, by dividing the door structure mass by the true outer surface (length of surface curvature) the normalized mass M_N was calculated. This approach was already used in the Concept Phase benchmarking. The normalized mass M_N for the ULSAC DH door structure is 2.23kg/m^2 below the target of 15.50 kg/m^2 (see Figure 10.1.2-1).

	Calculated Normalized Mass M_N (kg/m^2)	Mass Door Structure M_A (kg)	True Surface S_T (m^2)
ULSAC Target	15.50	12.23	0.789
ULSAC DH	13.27	10.47	0.789
Difference	-2.23	-1.76	

Fig. 10.1.2-1 Mass of ULSAC DH door structure

Figure 10.1.2-2 (See next page) shows the Validation Phase benchmarking data for the frameless door structures, and the calculated average value of the benchmarked Concept Phase door structure normalized mass. The door structure with the lowest mass found in the Concept Phase benchmarking is referred to as "framed best in class door" with a normalized mass of 17.01 kg/m^2.

	Calculated Normalized Mass M_N (kg/m^2)	Mass Door Structure M_A (kg)	True Surface S_T (m^2)
Door A	24.94	16.14	0.647
Door B	19.76	15.55	0.787
Door C	24.36	21.68	0.890
Avg. Benchmark Validation Phase	23.02		
Avg. Benchmark Concept Phase	19.74		
Framed Best in Class Concept Phase	17.01		
ULSAC Conept Phase Target	15.50		

Fig. 10.1.2-2 Benchmarking data

The normalized mass of the ULSAC DH door structure at 13.27 kg/m² is significantly below the target of 15.50 kg/m².

The results summary is shown in Figure 10.1.2-3. The graph visualizes the results from the benchmarking for mass in the Concept and Validation Phase in the form of a benchmarking range of normalized mass M_N stretching from 19.74 kg/m² (Concept Phase) to 23.02 kg/m² (Validation Phase).

The normalized mass value M_N of ULSAC DH door structure at 13.27 kg/m² is significantly below the target of 15.50 kg/m² and well into the target range. Compared to the benchmarking range stretching from M_N19.74 kg/m² to M_N23.02 kg/m², the ULSAC door structure shows a reduction in normalized mass M_N in the range of 30% to 42%.

Even when compared to the framed best-in-class door structure found in the Concept Phase benchmarking, the ULSAC DH door structure normalized mass is 22% lower.

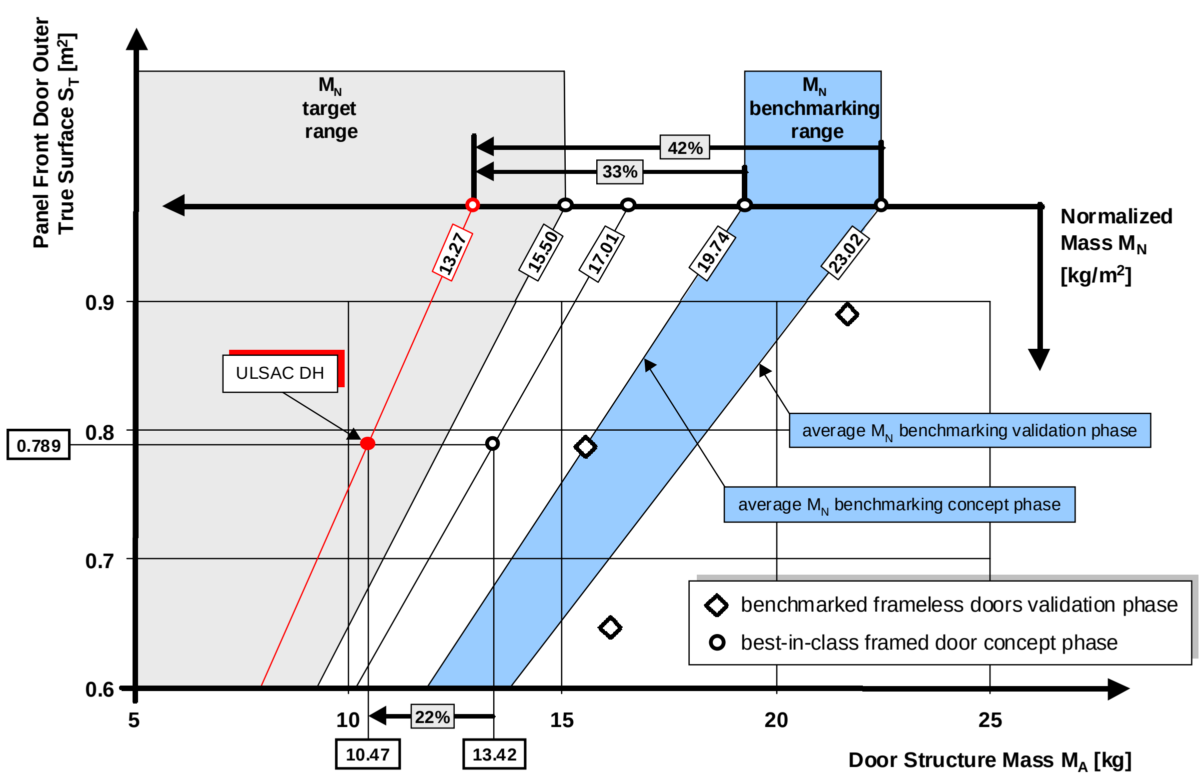


Fig. 10.1.2-3 Result summary

In the vertical door sag stiffness test, the door structure was placed in design position and constrained at the hinge locations.

10.1.3 Vertical Sag Stiffness

10.1.3.1 Test Description

In the test for vertical door sag stiffness, the door structure was placed in design position and constrained at the hinge locations with zero (0) degree of freedom attachments (see Figure 10.1.3.1-1). To measure the vertical downward position, one (1) deflection measurement device (Linear Voltage Potentiometers [LVP], displacement transducers) was positioned at the latch.

The door was loaded in the vertical downward direction, by pulling on a bolt placed adjacent to the door latch mechanism. (See Figure 10.1.3.1-2 on next page). In this test, the door was loaded in 44.3N increments up to a maximum of 996N and then unloaded back to zero (0) in 44.3N decrements.

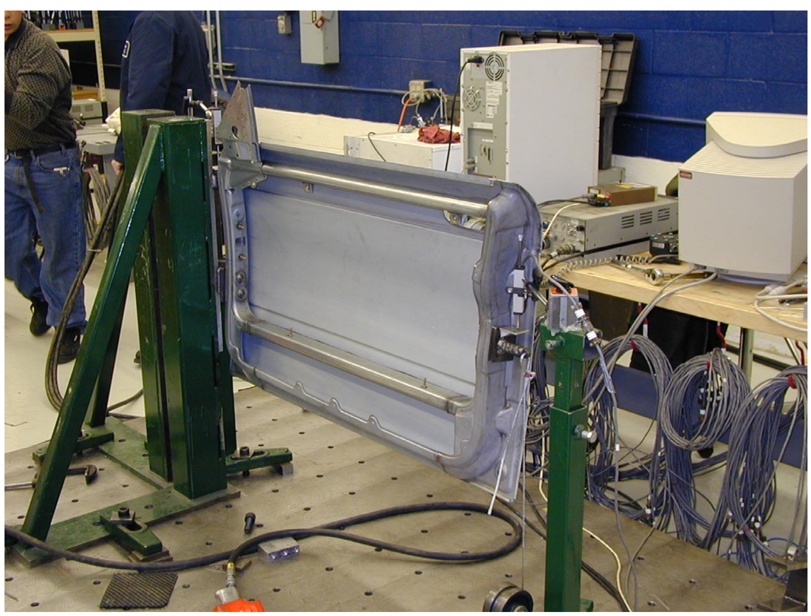


Fig. 10.1.3.1-1 Test set up vertical sag

The test results show the ULSAC DH door structure vertical sag stiffness at 156 N/mm.

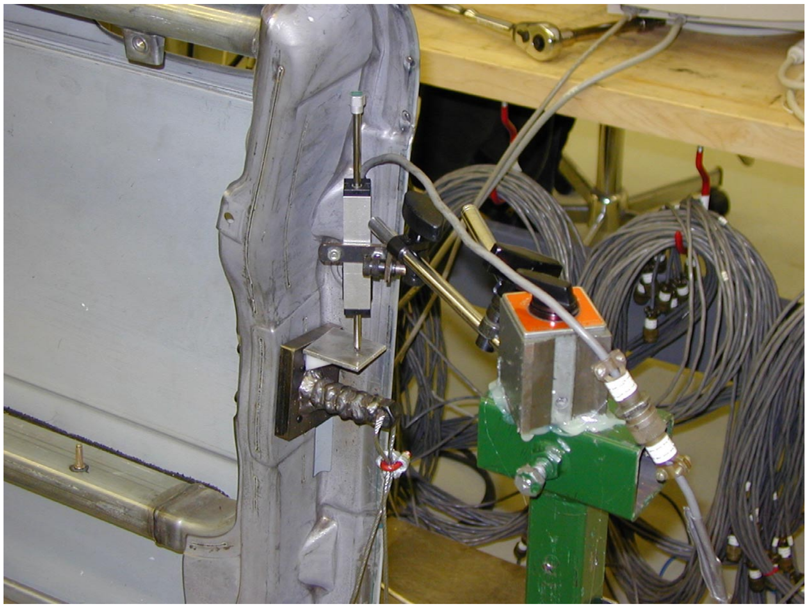


Fig. 10.1.3.1-2 Test set up at latch location

10.1.3.2 Test Results

Under the described test conditions (outside of vehicle) the test results (Fig. 10.1.3.2-1) show the ULSAC DH door structure vertical sag stiffness at 156 N/mm. The target of 287 N/mm set in the ULSAC Concept Phase was not achieved.

Downward Load	996 N
Indicator Location	Latch Vertical
Deflection	6.362 mm down
Set	0.347 mm down
Stiffness	156 N/mm

Fig. 10.1.3.2-1 Test results vertical sag stiffness

The benchmarking of frameless door structures shows that the ULSAC performs similar to other frameless door structures currently in production.

Figure 10.1.3.2-2 shows the deflection versus each incremental load up to the maximum load applied and also the decremental loads applied back to zero (0). The remaining set was measured at 0.347 mm down.

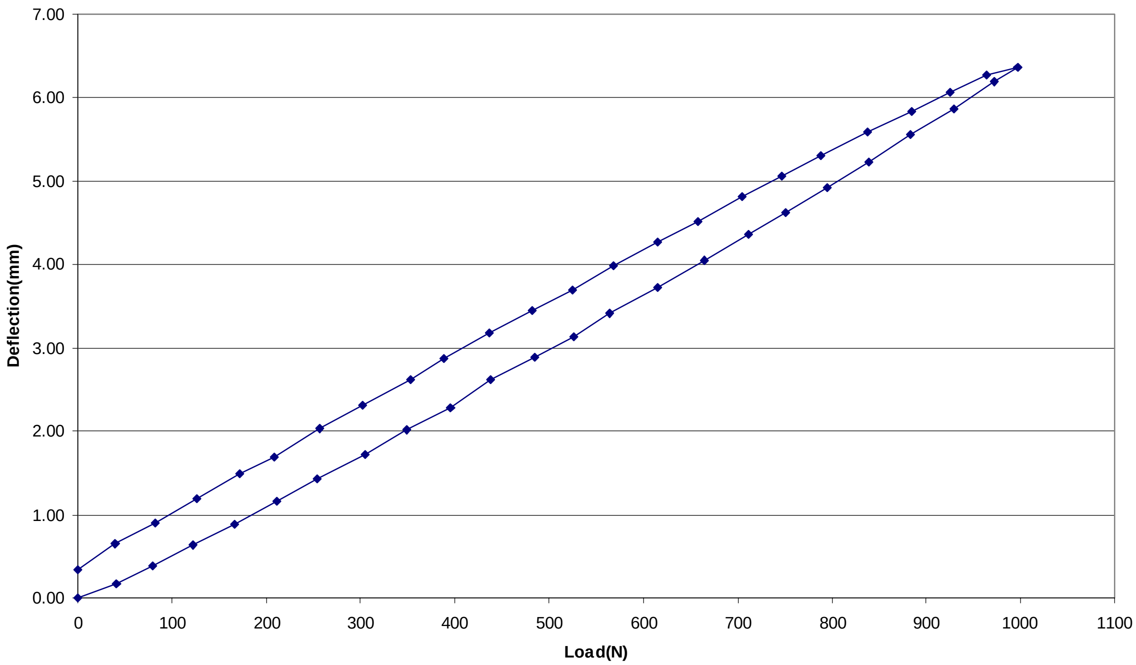


Fig. 10.1.3.2-2 Door sag incremental load versus deflection

The ULSAC Concept Phase target was set based on the available benchmarking data at that time and based on a mixture of door types. The benchmarking of frameless door structures in the validation phase shows that the ULSAC DH door structure performs similar compared to other frameless door structures currently in production.

The vertical door sag values of the benchmarked door structures were measured in the same test rig as the ULSAC DH door structure and not from the doors mounted to vehicles. The test set up did not include each door's specific hinges (Fig. 10.1.3.2-3).

Based on the benchmarking results the ULSAC DH door structure has achieved acceptable vertical door sag stiffness at significantly lower normalized mass M_N than the benchmarked frameless door structures.

	Door A	Door B	Door C	ULSAC DH
Vertical Door Sag Stiffness N/mm	109	194	497	157
Normalized Mass M^N kg/m_2	24.94	19.7	24.36	13.27

Fig. 10.1.3.2-3 Vertical sag stiffness comparison - ULSAC DH versus benchmarking

The ULSAC DH door structure was tested for upper and lower lateral stiffness by placing the door structure in design position.

10.1.4 Upper and Lower Lateral Stiffness

10.1.4.1 Test Description

The ULSAC DH door structure was placed in design position and constrained at the hinges. At the latch location, the door structure was constrained with one degree of freedom to allow rotation about the X-axis. The test set up for upper lateral stiffness is shown in Figure 10.1.4.1-1. The load was applied on the inboard side of the door structure at the Beltline Reinforcement Tube, pushing the door in the outboard direction. A maximum load of 181 N was applied in 22.3 N increments and brought back to zero (0) in 22.3 N decrements. Two (2) Linear Voltage Potentiometers (LVP) displacement transducers were used on the door outer panel to measure deflections. The top LVP displacement transducers was placed in line with the load point and the lower LVP displacement transducers was positioned vertically down on the Panel Front Door Outer.

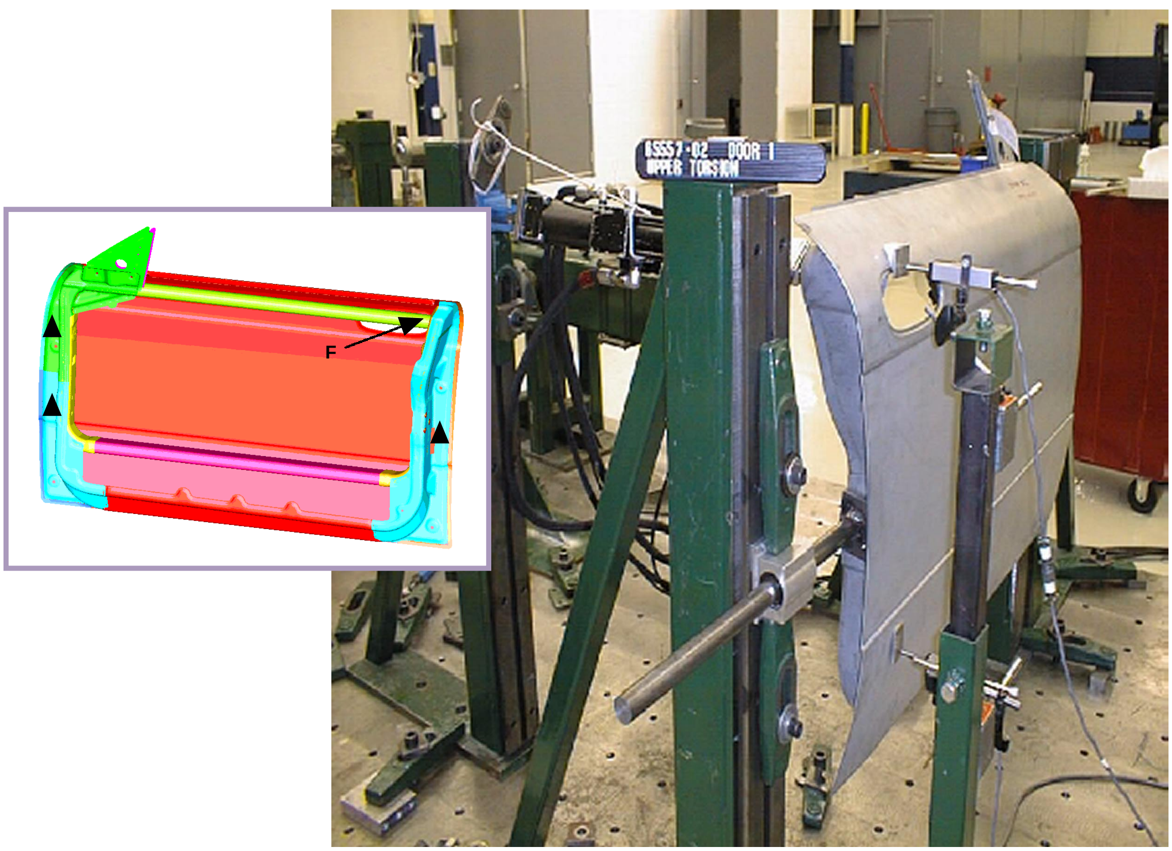


Fig. 10.1.4.1-1 Test set up for Upper lateral stiffness

Upper and lower lateral stiffness test were performed in order to compare structural perfromance for the ULSAC DH door structure.

The test set up for the lower lateral stiffness is shown in Figure 10.1.4-2. In this test, the load is applied at the lower left corner on the outboard surface of the door, pushing the door in the inboard direction. A maximum load of 180 N was applied in 22.15 N increments and then brought back to zero (0) in 22.15 N decrements. Two (2) LVP were used on the door inside to measure deflections. The bottom LVP was placed in line with the load and the top LVP displacement transducer was placed vertically up onto the door structure.

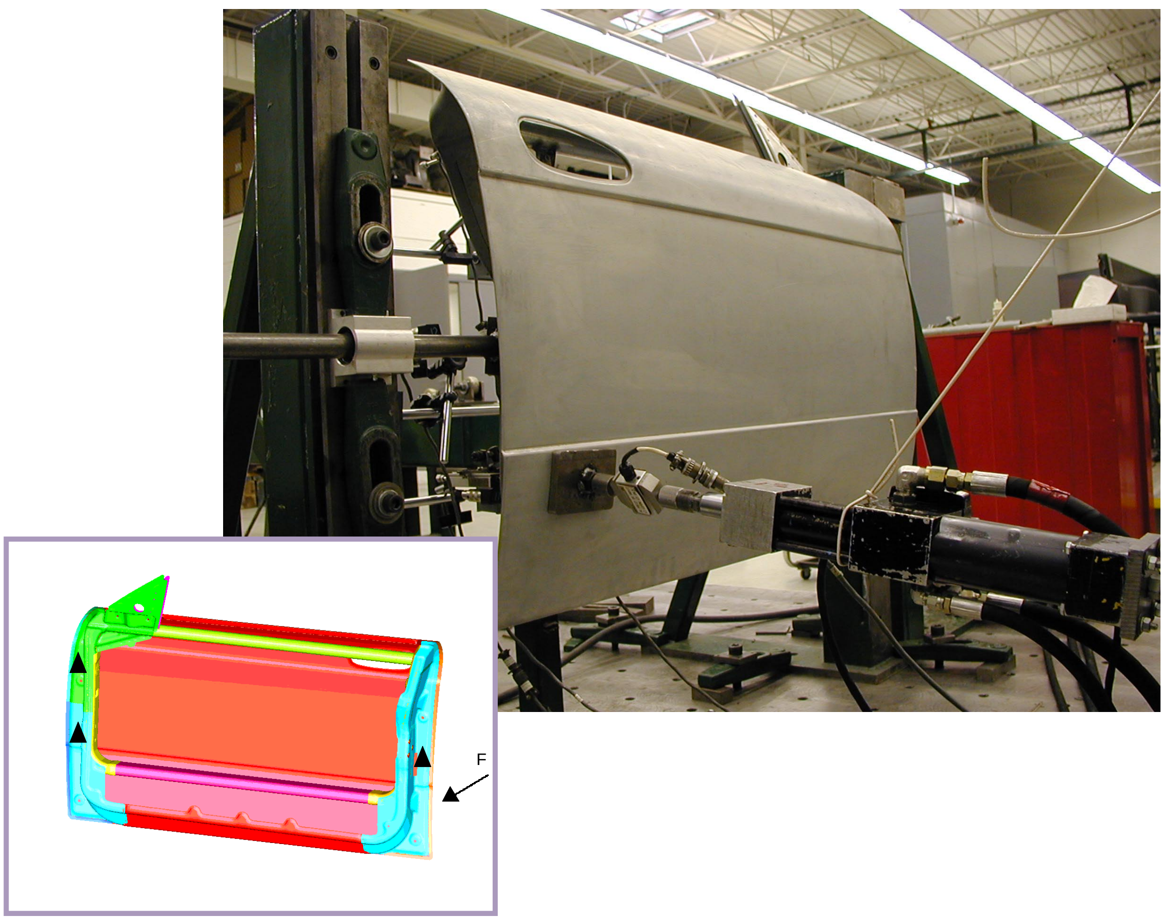


Fig. 10.1.4.1-2 Test set up for lower lateral stiffness

The ULSAC DH door structure shows significantly higher values for upper and lower lateral stiffness when compared to the Concept Phase targets.

10.1.4.2 Test Results

The ULSAC DH door structure shows significant higher values for upper and lower lateral stiffness when compared to the target as set in the ULSAC Concept Phase. Compared to the Validation Phase benchmarking of frameless door structures, these values show that the target set in the Concept Phase (based on values from a mixture of door types) appears not to be state-of-the-art and set lower than current frameless door structures perform. The ULSAC DH door structure test results (Figure 10.1.4.2-1) show state-of-the-art upper and lower lateral stiffness compared to the benchmarked frameless door structures.

Loadcase	Door A	Door B	Door C	ULSAC DH	ULSAC Concept Phase Target
Upper Lateral Stiffness Nm/deg	352	197	188	259	127
Lower Lateral Stiffness Nm/deg	467	309	188	261	127

Fig. 10.1.4.2-1 Upper and lower lateral stiffness benchmarking results

10.1.5 Testing for Quasi-Static Side Intrusion

In the ULSAC Program, it was important to demonstrate that the ULSAC DH door structure can provide sufficient side intrusion protection at low mass. To test the ULSAC DH door structure for its safety, a quasi-static side intrusion test, similar to FMVSS 214 Standard was performed. In the FMVSS 214 test for quasi-static side intrusion, the door is tested on a complete vehicle.

As the ULSAC door structure does not fit in any production vehicle, it could not be tested in accordance with the FMVSS 214 standard and the results are not directly comparable to the requirements of FMVSS 214.

10.1.5.1 Test Description

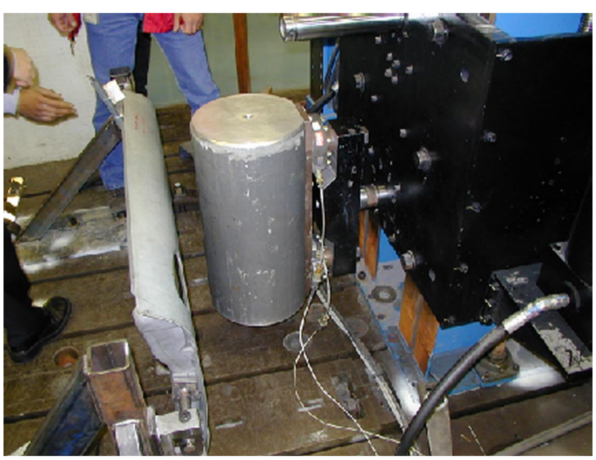


Fig. 10.1.5.1-1 Side intrusion test set up

Although the ULSAC DH door structure can not be tested for FMVSS 214 standards, a test with similar requirements was performed.

In the ULSAC Program quasi-static intrusion test, the door structure was mounted to a rigid test rig representing a rigid front Hinge pillar and B-pillar. At the hinge locations, the door was bolted to rigid fixtures representing the hinges restrained in all directions, except rotation around the vertical Z-axis. At the latch location, the door was restrained allowing rotation about the vertical Z-axis. This allowed the door hinges to pivot while keeping the simulated door latch rigid. The complete assembled test rig was positioned and bolted to the bed plate in front of the impact head with the vertical centerline of the door structure lined up with the impact head centerline. The door height was adjusted, so that the lower edge of the impactor lined up 5 inches above the lower edge of the door structure.

The impactor head is 12 inches (304.8 mm) in diameter and 24 inches (609.6 mm) in length, propelled with a 4.45 kN, 24 inch (609.6 mm) stroke, linear hydraulic actuator. The impact head was cycled into the door structure at a rate of 5 inch (127 mm) per second (0.026mph) 0.0416 km/h for a total of 18 inches (457.2 mm) of displacement. Two (2) load cells with capacities of 4.45 kN and a Linear Variable Differencial Transformer (LVDT) were used to generate the data.

The force versus displacement over the deformation of the door structure was recorded according to FMVSS 214. The average initial crush resistance at 6 inches (152.4 mm) of intrusion and the intermediate crush resistance at 12 inches (304.8 mm) of intrusion was calculated. The peak crush resistance, the largest force appearing over the entire 18 inches (457.2mm) of crush distance was recorded.

10.1.5.2 Test Results

The ULSAC door structure performance is shown in Figure 10.1.5.2-1. The results are in a close range to the FMVSS 214 requirements and indicates that the ULSAC door structure would meet the requirement when mounted into a complete vehicle.

	ULSAC DH	FMVSS 214
Initial Crush Resistance at 6" (kN) *	8.18	10.01
Intermediate Crush Resistance at 12" (kN) *	11.51	15.57
Peak Crush Force (kN)	38.9	31.14

* Average Force

Fig. 10.1.5.2-1 ULSAC DH door structure results

The benchmarking of the frameless doors in the Validation Phase also included testing of the same three (3) doors under the same quasi-static side intrusion crush test conditions as the ULSAC door structure.

This benchmarking was done to demonstrate that the ULSAC door structure performs as well as the benchmarked doors. Since these doors are sold in vehicles on the US market, they must meet the FMVSS 214 requirements when tested on complete vehicles.

Furthermore, by demonstrating that the ULSAC DH door structure performs as well as the benchmarked doors would satisfy the ULSAC Program objective that the ULSAC DH door structure was to be designed to meet the quasi-static FMVSS 214 requirements.

The summary of the results of the quasi-static side intrusion tests of the benchmarked frameless doors and the ULSAC DH door structure is shown in Figure 10.1.5.2-2.

	FMVSS 214	Door A	Door B	Door C	ULSAC DH
Initial Crush Resistance at 6" (kN) *	10.01	8.55	6.18	7.33	**8.18**
Intermediate Crush Resistance at 12" (kN) *	15.57	7.73	11.21	13.33	**11.51**
Peak Crush Force (kN)	31.14	15.17	25.56	24.59	**38.90**

* Average Force

Fig. 10.1.5.2-2 Summary of results

The design integration allows the reduction of mass by eliminating the need for a side intrusion protection beam.

Figure 10.1.5.2-3 shows the force over the complete displacement of the benchmarked doors and the ULSAC DH door structure.

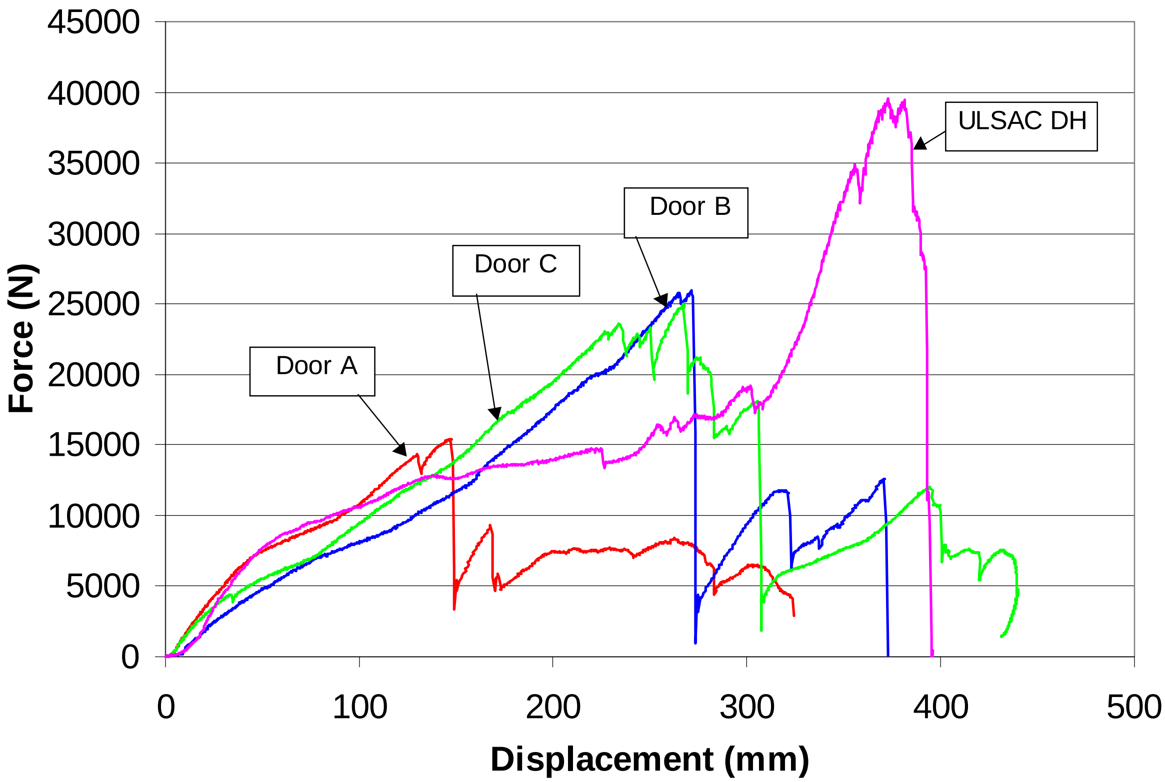


Fig. 10.1.5.2-3 Force/displacement

None of the three (3) benchmarked frameless doors meets the crush resistance values FMVSS 214 requires for quasi-static side intrusion, when tested in the rigid test rig under the same conditions as the ULSAC DH door structure. The test results show, the ULSAC DH door structure with similar performance when compared to the benchmarked door structures. The peak crush force measured for the ULSAC DH door structure is significantly higher than any of the measured benchmarked door structures and exceeds the FMVSS 214 requirements.

This result confirms that mass reduction, without compromising safety, can be achieved using the unique and patented ULSAC DH door structure design features.

The ULSAC design of the inner door frame integrates two (2) functions. It provides the door structure and its ultra high strength steel horizontal tubes function as side intrusion beams. The design eleminates the need for the addition of a side intrusion beam as found in many other door designs. Instead, the outer belt reinforcement and lower tube serve this function, while also being integral parts of the door structure and allows the reduction of mass.

10.2 Dent Testing

10.2.1 Scope of Work

The dent resistance of the Panel Door Outer is one of the key factors of customer satisfaction. Therefore, three steel qualities/grades were nominated for the ULSAC Front Door Outer Panel. Dent resistance testing was performed to determine the best choice for this design.

10.2.2 Targets

Automotive outer-body panels are designed to meet numerous performance requirements, dent resistance being one of them. Dent resistance can be divided into quasi-static and dynamic denting. The quasi-static denting simulates dent phenomena that occurs at low indent velocity, such as palm-printing, elbow marks, or plant handling. Dynamic denting simulates loadings at higher indenter velocities, such as stone and hail impact, shopping carts and door-to-door impact. It is difficult to define and measure the visibility of a dent.

Another important factor is oil-canning, which occurs as a sudden reversal of curvature in the panel when a certain load is applied. Therefore, it was necessary to examine the performance of dynamic and quasi-static dent resistance, as well as oil canning, on the ULSAC doors.

The ULSAC Consortium decided to determine dynamic dent resistance behavior at Corus Netherlands in the Product Application Centre at Ijmuiden (IJTC) and Corus United Kingdom in the Welsh Technology Centre at Port Talbot (WTC). National Steel, USA, Product Application Center was chosen by the Consortium to perform static dent resistance testing and oil canning.

The ULSAC Consortium decided to determine dynamic dent resistance behavior at Corus Netherlands, Corus UK and National Steel, USA.

10.3 Test Set-up at Corus UK and Corus NL

10.3.1 Comparison of Dynamic Dent Testing Methods

There are different methods of dynamic dent resistance testing. As of today, there is no standardization concerning the two different testing methods used at Corus NL and Corus UK, round robin test that was performed on the different material samples. The comparison of these test results led to the conclusion that the ranking of the materials is the same in both tests. For both tests, thickness is the dominant parameter. The tests devices are based on the same principles, but there are some differences in the test methodology. In the following table (see Figure 10.3.1-1) the range of test parameters, which could be used in principle, is shown.

	Corus Port Talbot (WTC)	Corus Ijmuiden (IJTC)
Bullet diameter, mm	18.0	6.0
Test velocity range, mph	30 - 60	60 - 120
Width of area around the dent taken as reference, mm	± 15	± 15 (flat sheet) Software used to obtain continuous reference for curved panels
Test energy, J	1 - 9 (at impact)	0.2 - 1.2 (absorbed)
Rebound velocity - measured	No	Yes
Measurement method	Manual Depth measured using single probe Flat sheet mounted in square frame, 4 square areas for testing in the frame of free surface 175 x 175 mm	Automatic Profile measured to find depth and shape Flat sheet mounted in circular frame, free surface of 50 mm diameter

Fig. 10.3.1-1 Comparison of dent testing methods

The IJTC test stimuated stone chipping, whereas the WTC test stimulated hailstones.

The next table (see Figure 10.3.1-2) shows the parameters used for dynamic dent resistance testing of the ULSAC DH doors.

	IJTC	WTC
Bullet Diameter	6 mm	18 mm
Bullet Mass	0.88 g	23.8 g
Bullet Speed	47.6 m/s 170 km/h	22.3 m/s 80 km/h
Bullet Energy	1 J	5.9 J

Fig. 10.3.1-2 Test conditions for ULSAC DH door structures

Due to the parameters chosen, the IJTC test simulates stone chipping, while the WTC simulates hailstones. Each door was tested on two points indicated on the door plan (see Figure 10.3.1-3).

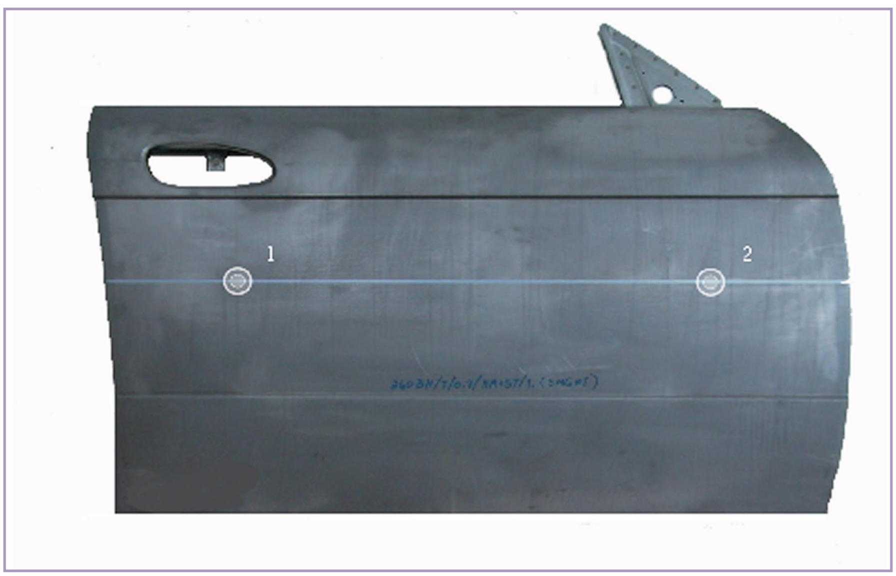


Fig. 10.3.1-3 Target zones for dent testing

The materials chosen for dent testing, for the panel front door outer were, BH210, BH260 and DP600.

10.3.2 Material for Panel Front Door Outer

Three different materials were selected for dent testing. The materials chosen were BH210, BH260, and DP600. All materials were tested in two (2) thicknesses: 0.6 and 0.7 mm. Three (3) duplicate ULSAC DH door structures were manufactured for each set of variables, to provide a statistical basis.

In total, 18 ULSAC DH doors were manufactured and available for testing. The 18 doors were divided for the two testing locations according to Figure 10.3.2-1.

Material	(mm)	Doors for Testing
BH 210	0.6	IJTC
BH 210	0.6	WTC
BH 210	0.6	WTC
BH 210	0.7	IJTC
BH 210	0.7	IJTC
BH 210	0.7	WTC
BH 260	0.6	WTC
BH 260	0.6	IJTC
BH 260	0.6	WTC
BH 260	0.7	IJTC
BH 260	0.7	IJTC
BH 260	0.7	WTC
DP 600	0.6	IJTC
DP 600	0.6	WTC
DP 600	0.6	WTC
DP 600	0.7	IJTC
DP 600	0.7	IJTC
DP 600	0.7	WTC

Fig. 10.3.2-1 Door specification and test locations

10.3.3 Dent Testing Product Application Centre at IJmuiden (IJTC)

The dynamic dent testing was carried out using the Dynamic Impact Tester (DIT) shown in Figure 10.3.3-1. The DIT is an air gun which fires a bullet to car body sheets or parts, in this case ULSAC doors.

At IJTC, the kinetic energy of the bullets was 1 Joule (bulletspeed 47.6 m/s). The bullet (diameter 6 mm, mass 0.88 gram) was placed in the barrel. The pressure in the valve and the position of the bullet in the barrel determine the speed of the bullet. The impact and the rebound speed of the bullet were measured by two windows with sensor units, which record the time of flight over a fixed 100 mm distance. The doors were positioned on two wooden beams and fixed by two bolts (See Figure 10.3.3-).

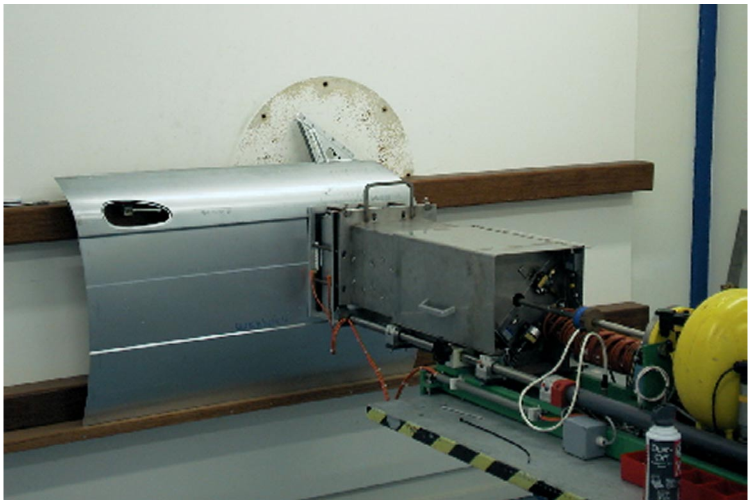


Fig. 10.3.3-1 Dynamic impact tester IJTC

The shape and depth of the dent was measured with a Mitutoyo 3D CNC Coordinate Measuring Machine (accuracy ± 0.02 mm) at Mitutoyo Veenendaal/Netherlands (See Figure 10.3.3-2).

Fig. 10.3.3-2 Mitotoyo 3D measuring machine

Contours of the dent were measured in a longitudinal directional and a transverse direction.

First, the deepest point of each dent was located. Two contours of the dent are then measured, one in the longitudinal direction and the one in the transverse direction. In Figure 10.3.3-3 and Figure 10.3.3-4, two (2) contour profiles are given. In the longitudinal direction, the door is always flat. In the transverse direction, the door has a curvature. To determine the dent depth in the longitudinal direction, the dent depth was measured over a distance of 50 mm, 25 mm before and 25 mm after the deepest point of the dent. In the transverse direction, the contour was measured over a distance of 100 mm, 50 mm before and 50 mm after the deepest point. By scaling this contour in the Z-direction, it was possible to determine the beginning and the end of a dent. By fitting a curve through the measured contour outside the dent area, the original shape of the product can be estimated. By subtracting this contour from the contour after denting, the resulting dent shape is obtained (see Figure 10.3.3-4). The summary of the measured dent depths is given in Figure 10.3.3-5 (see next page).

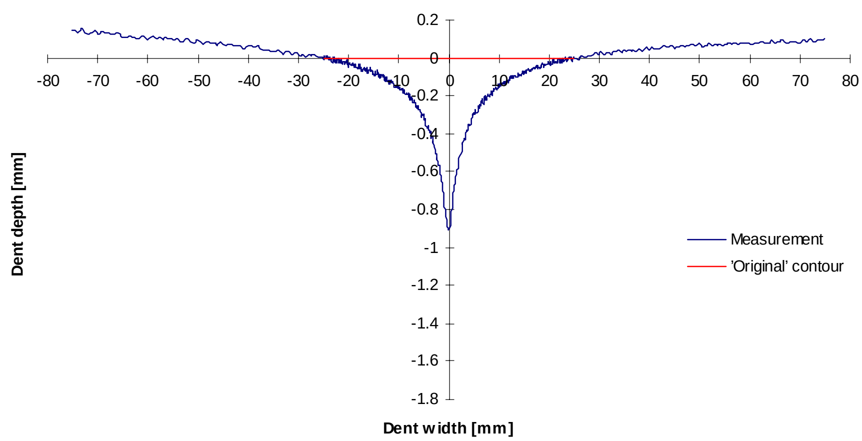


Fig. 10.3.3-3 Dent measurment in longitudinal direction of the door

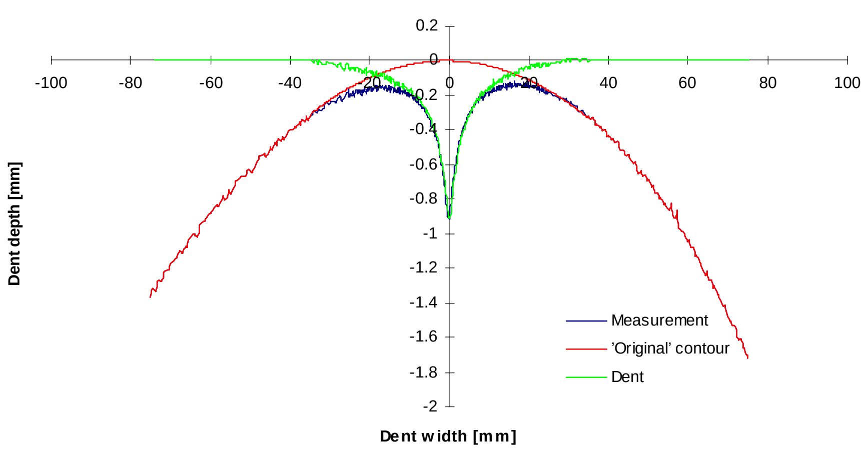


Fig. 10.3.3-4 Dent measurment in transverse direction of the door

ID	Dent Depth Longitudinal Pos. 1 (mm)	Dent Depth Transverse Pos. 1 (mm)	Dent Depth Longitudinal Pos. 2 (mm)	Dent Depth Transversal Pos. 2 (mm)
BH 210 / 0.6	1.067	1.070	1.047	1.050
BH 210 / 0.7	0.819	0.839	0.812	0.818
BH 210 / 0.7	0.831	0.828	0.830	0.841
BH 260 / 0.6	0.896	0.911	0.912	0.911
BH 260 / 0.7	0.739	0.740	0.742	0.759
BH 260 / 0.7	0.737	0.747	0.738	0.726
DP 600 / 0.6	0.863	0.880	0.846	0.862
DP 600 / 0.7	0.747	0.733	0.724	0.754
DP 600 / 0.7	0.738	0.747	0.711	0.723

Fig. 10.3.3-5 Measured dent depth at IJTC

10.3.4 Welsh Technology Centre at Port Talbot

The dynamic dent testing at WTC was carried out with a similar procedure as at IJTC. The doors were mounted in a jig, which was clamped inside the dent “cage.” Two jig fixture points permitted the denting of each door in the two positions. The door panel and the end of the firing barrel were separated by a distance of 160 mm. The bullet is 18 mm in diameter and 23.8 gram in mass. The firing devise uses air pressure to shoot the bullet against the Panel Front Door Outer surface. The exact speed was calculated using the time of the bullet traveling through a 100 mm distance prior to impact.

The resulting dent depth was measured using a Mitutoyo height gauge which stood on a platform over the door panel (See Figure 10.3.4-1). Before each measurement, the platform was positioned just above the deepest point of the dent and the height gauge calibrated using a 30 mm diameter reference to the original contour of the panel. The dent depth could then be measured (See Figure 10.3.4-2).

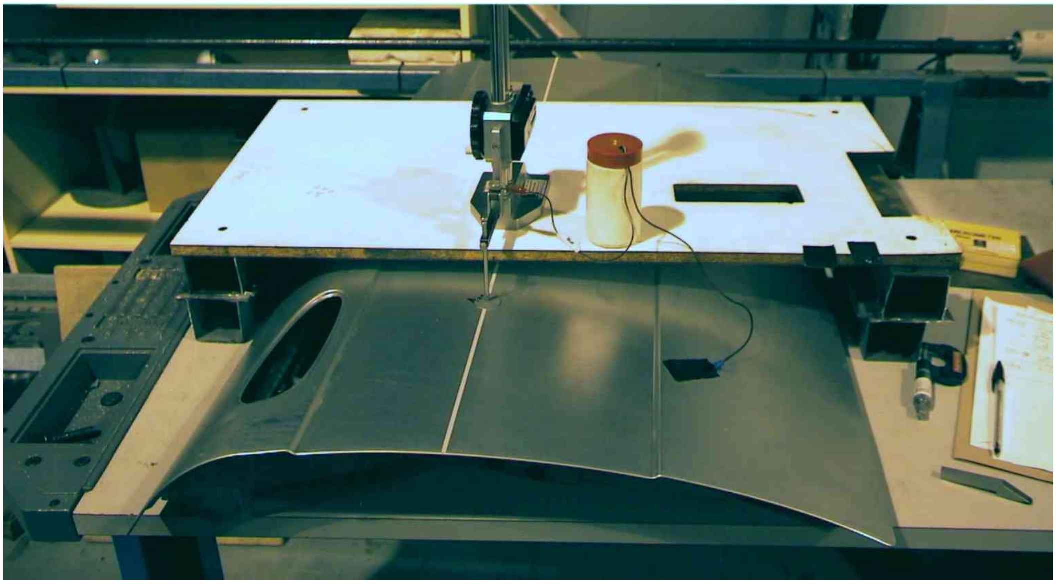


Fig. 10.3.4-1 Dent depth measurement at WTC

ID	Dent Depth Pos. 1 (mm)	Dent Depth Pos. 2 (mm)
BH 210 / 0.6	1.59	1.58
BH 210 / 0.6	1.62	1.62
BH 210 / 0.7	1.32	1.47
BH 260 / 0.6	1.48	1.41
BH 260 / 0.6	1.55	1.46
BH 260 / 0.7	1.24	1.26
DP 600 / 0.6	1.24	1.36
DP 600 / 0.6	1.41	1.37
DP 600 / 0.7	1.10	1.16

Fig. 10.3.4-2 Measurement dent dephs at WTC

The exact material thickness of the material at the dent location was measured.

10.4 Discussion of Dynamic Dent Testing Results at Corus NL & Corus UK

10.4.1 Thickness Measurement

Before denting the thickness of the material at the dent location was measured using an ultrasonic apparatus. In Figure 10.4.1-1, the ordered and delivered thickness is shown versus the thickness at the test locations. Due to the fact that there is no large difference between these values, the conclusion can be drawn that the strain in the panel is as low it can be found on door outer panels with similar shape.

Material ID code	Order Thickness (mm)	Flat Sheet Thickness (mm)	Stamped Thickness pos. 1 [mm]	Stamped Thickness pos. 2 [mm]
BH 210	0.6	0.593	0.596	0.583
BH 210	0.7	0.707	0.692	0.687
BH 260	0.6	0.612	0.593	0.591
BH 260	0.7	0.702	0.689	0.679
DP 600	0.6	0.597	0.585	0.584
DP 600	0.7	0.697	0.680	0.673

Fig. 10.4.1-1 Thickness measurement

10.4.2 Mechanical Property Results

In order to determine the effect of work hardening and bake hardening applied for the door outer panels, one of each ULSAC Panel Front Door Outer strength/thickness combination was tested. Sections between locations "D" and "C" (see fig. 10.5-3, page 24) were taken from the finished door once the dent resistance tests were done. ASTM tensile specimens were cut and prepared in "L" (along length of door), "T" (top to bottom of door) and "D" (diagonal) directions. Results of these tensile tests are shown in Figure 10.4.2-1 (See following page). Comparing the results with the material properties of the sheet material (see Chapter 6, Figure 6.3.1-1), it is obvious that the dual phase material DP600 has the largest work and bake hardening effect. An increase of about 140 MPa could be found here. For both BH grades, the increase is between 50 and 70 MPa compared to the virgin material.

According to the forming simulation and the strain analysis measurement, the conclusion can be drawn for these results that there is a certain strain even in this flat middle area of the door from which the test samples were taken from.

The thickness and the geometry of the panel have a significant influence on the dent depth.

Table I. Mechanical Property Results

Material	Sample	Thickness Bare (mm)	Yield Strength (MPa)	Yield Point Elongation (MPa)	Tensile Strength (MPa)	Uniform Elongation (%)	Total Elongation (%)	n Value	K Value (MPa)	Strain Range for n, K (%)
BH210-0.6	L	0.586	318	None	424	16.7	29.8	0.167	670	10.0-16.7
BH210-0.6	D	0.587	317	None	401	18.1	31.9	0.164	635	10.0-18.1
BH210-0.6	T	0.587	338	None	428	15.9	30.2	0.160	668	10.0-15.9
BH210-0.7	L	0.684	284	0.9	375	18.1	33.6	0.166	591	10.0-18.1
BH210-0.7	D	0.684	303	4.1	383	20.0	32.2	0.156	593	10.0-20.0
BH210-0.7	T	0.682	303	3.9	370	17.0	33.0	0.156	578	10.0-17.0
BH260-0.6	L	0.587	340	2.0	416	13.6	24.7	0.121	607	10.0-13.6
BH260-0.6	D	0.595	336	3.2	408	13.9	26.1	0.134	612	10.0-13.9
BH260-0.6	T	0.586	338	3.5	410	12.5	24.8	0.126	605	10.0-12.5
BH260-0.7	L	0.684	311	2.5	403	15.5	30.0	0.151	624	10.0-15.5
BH260-0.7	D	0.691	305	3.1	402	14.7	29.3	0.156	624	10.0-14.7
BH260-0.7	T	0.689	306	2.5	399	17.7	31.7	0.156	623	10.0-17.7
DP600-0.6	L	0.583	482	None	653	12.1	20.8	0.125	964	10.0-12.1
DP600-0.6	D	0.578	482	None	662	13.2	22.1	0.123	971	10.0-13.2
DP600-0.6	T	0.580	489	None	673	11.9	20.2	0.115	971	7.0-11.9
DP600-0.7	L	0.680	474	None	632	13.7	22.4	0.140	961	10.0-13.7
DP600-0.7	D	0.673	480	None	643	14.7	23.2	0.137	971	10.0-14.7
DP600-0.7	T	0.675	487	None	652	14.1	22.0	0.130	970	10.1-14.1

Note: Samples tested with coating. Coating only removed to establish thickness for cross-sectional area.

Fig. 10.4.2-1 Mechanical property results

10.4.3 Dent Depth Comparisons

The results of the dynamic dent testing is shown in Figure 10.4.3-1, by comparing the dent depths achieved at IJTC and WTC. The much deeper dents measured by WTC, compared with those measured by IJTC, is a result of denting with a much larger bullet at lower velocity. This conclusion was drawn from earlier tests on flat panels. It is known that the thickness and the geometry of the panel have a large influence on dent depth.

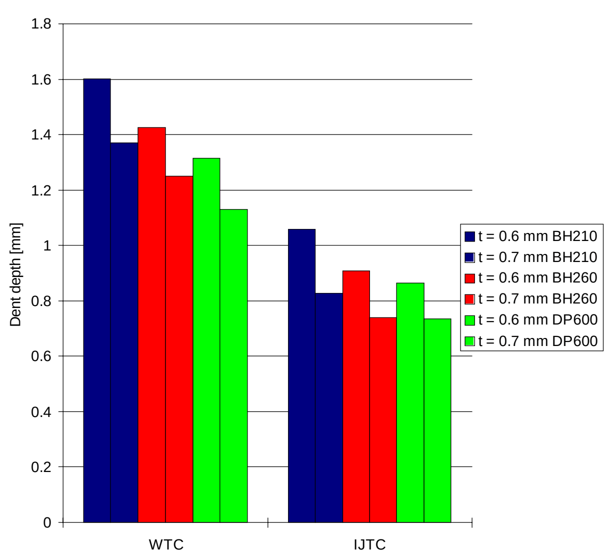


Fig. 10.4.3-1 Results of Dent Testing at IJTC and WTC

In consequence, the results in this report are only valid for the particular ULSAC door geometry. In both tests, the measured dent depth of BH210 with a thickness of 0.7 mm is nearly equal to the dent depth of DP600 with a thickness of 0.6 mm. In both tests the ranking of the materials is the same. The performance of the material DP600 was the best for the ULSAC door design but very close to the performance of BH260, as well.

10.5 Test Procedure at National Steel, USA

The 18 assembled doors tested at Corus NL and Corus UK were then sent to National Steel for testing. The test procedure was performed in accordance with procedures extablished by North America's Auto/Steel Partnership (A/SP), as set forth in the A/SP's report entitled, "Procedures for Evaluating Dent Resistance of Steel Automotive Panels, Version 1.0 – June 1999." This test consists of an incremental loading of the test panel, using successively greater loads, while measuring the dent depth resulting from each load increment. A 25mm steel hemisphere is used as an indenter. The indenter speed was 50 mm/min. The dent depth for each increment is determined by measuring the indenter position after each increment and comparing this with the indenter position before the first increment. Each indenter position is determined with a 5 N load on the indenter to assure solid contact with the panel. Testing is usually performed with increments of increasing load until a load of 250 N is reached. In these tests, the first increment continued to a load of 50 N. On subsequent increments, the load was increased by 18 N until a load of 260 N was reached.

The National Steel dent tester uses a servo-hydraulic load frame to apply the force (See Figure 10.5-1). The LVDT in the actuator applying the force is used to measure punch position.

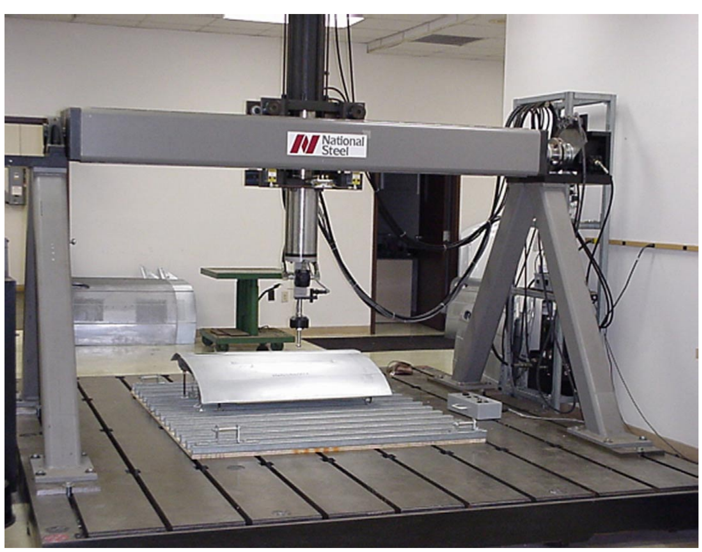


Fig. 10.5-1 National Steel dent tester

Additionally to the incremental testing, a single increment dent test was performed.

In addition to the incremental testing, a single increment dent test to 260 N was performed to record the load versus deflection curve for the panel. This curve and the behavior of the panel gives an indication of the oil canning sensitivity described previously.

Finally, dynamic incremental dent tests were also performed on each door. Each increment of the test represented a deeper penetration of the indenter into the panel. The dent depth from each increment was determined in a manner similar to that used for the quasi-static dent test. The indenter speed during each increment was 250 mm/s. The dent depth was measured using an indenter speed of 50 mm/min. The loads measured during the dynamic tests were corrected for effects of acceleration using an accelerometer attached close to the head of the indenter.

Panels were mounted for testing using a fixture that supports the panel on the tubular frame approximately at the four corners of the panel. The panel was tied to the mounting fixture using four hand-tightened turnbuckles attached close to the supporting points on the panel (See Figure 10.5-2)

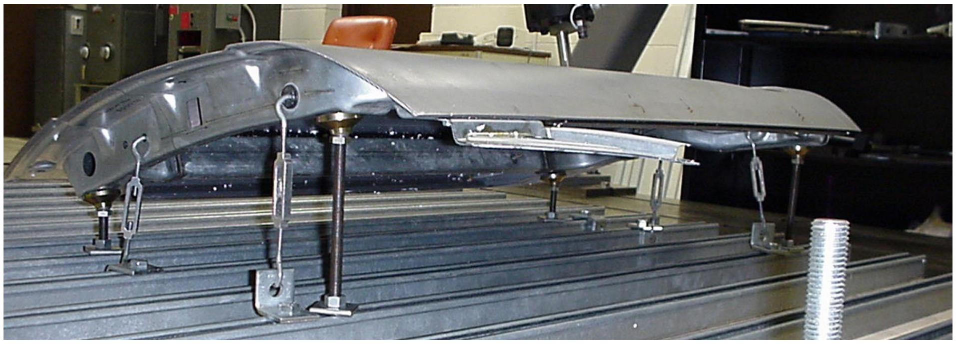
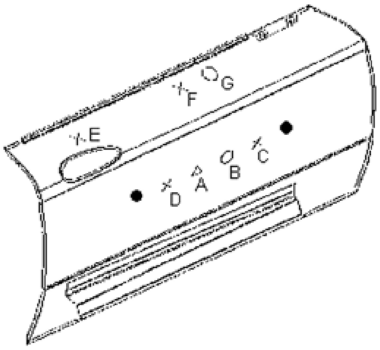


Fig. 10.5-2 Mounting of panel in dent tester

Testing was performed at the points shown in Figure 10.5-3. The four test points on the central part of the panel were spaced evenly between the two locations previously tested for dynamic dent resistance by Corus NL & UK.



Legend

C, D, E, F = Static
B, G = Dynamic
A = Oil Canning
• = Prior Dynamic Testing

Fig. 10.5-3 Test locations

The critical dent load was defined according to the Auto Steel Partnership's procedure.

10.6 Test Results at National Steel, USA

10.6.1 Quasi-Static Incremental Testing

The test results from the quasi-static incremental dent test are shown in Figure 10.6.1-1, Quasi-static Incremental Dent Test Results. In this table a critical dent load is defined according to the Auto Steel Partnership's (A/SP) procedure mentioned earlier. This critical dent load incorporates a remaining dent depth of 0.1 mm. If this critical load is above 130 N, the test is adequately fulfilled. If the load is above 150 N, the test result is excellent.

Table I. Quasi-Static Incremental Dent Test Results

	Location C		Location D		Location E		Location F	
Panel	Stiffness (N/mm)	Critical Dent Load at 0.1 mm Dent Depth (N)	Stiffness (N/mm)	Critical Dent Load at 0.1 mm Dent Depth (N)	Stiffness (N/mm)	Critical Dent Load at 0.1 mm Dent Depth (N)	Stiffness (N/mm)	Critical Dent Load at 0.1 mm Dent Depth (N)
BH210-0.6	12	135	10	123	27	70	29	85
BH210-0.7	17	169	17	143	78	114	58	140
BH260-0.6	12	157	10	139	30	104	30	130
BH260-0.7	17	182	17	171	44	116	46	148
DP600-0.6	17	205	15	186	45	131	33	175
DP600-0.7	20	218	22	211	76	139	53	184

Fig. 10.6.1-1 Quasi-static incremental dent test results

The quasi-static incremental dent tests reveal greater dent resistance in the mid-door region than the region at the top of the door. This is a result of the shape of this area wtih greater stiffness at the top of the door, which limits the amount of elastic deformation that can take place. A comparison of the quasi-static dent resistance location C and location E is shown in Figure 10.6.1-2, Quasi-static dent resistance results for 0.1 mm.

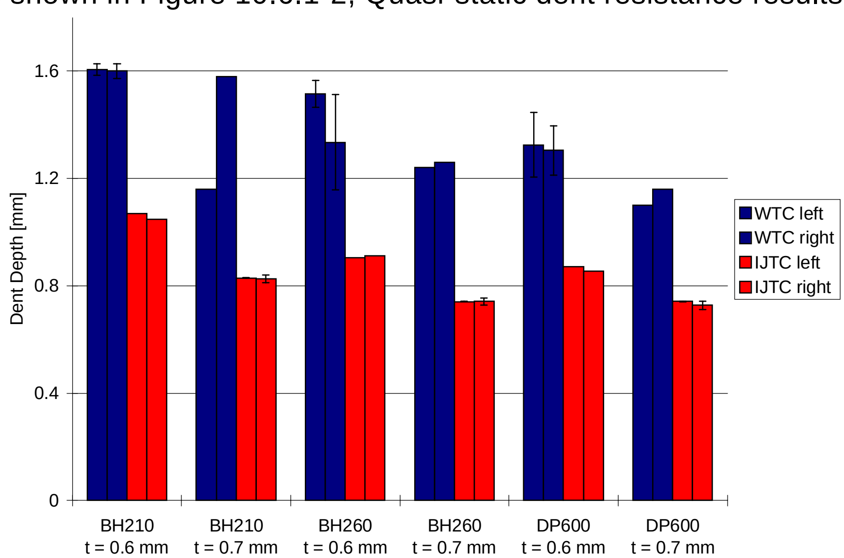


Fig. 10.6.1-2 Quasi-static dent resistance test results for 0.1 mm

Oil canning may be observed as a sudden reversal of the curvature of panel.

10.6.2 Quasi-Static Single Load Testing

As described earlier during this test a single increment load of 260 N is applied. During this procedure, oil canning may be observed as a sudden reversal of the curvature of the panel accompanied by an audible indication of this sudden reversal.

Test results for the different material/ thickness combinations are shown in Figures 10.6.2-1 to 10.6.2-6 (also shown on following page) and are examples from all 18 doors tested.

Representative single increment load – deflection curves from location A.

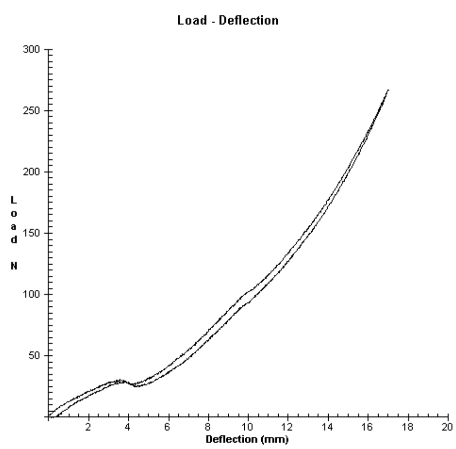


Fig. 10.6.2-1 BH210, 0.6 mm

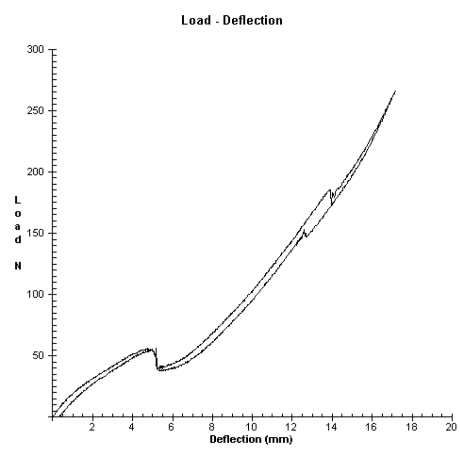


Fig. 10.6.2-2 BH210, 0.7 mm

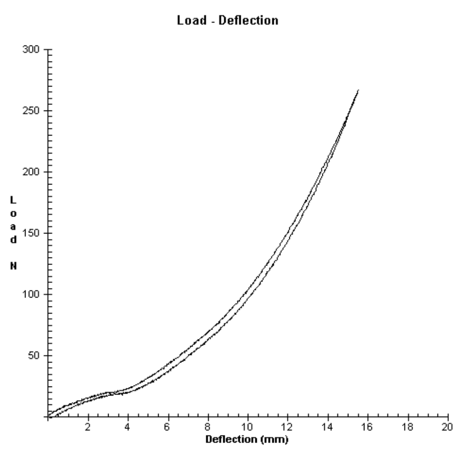


Fig. 10.6.2-3 BH260 0.6 mm

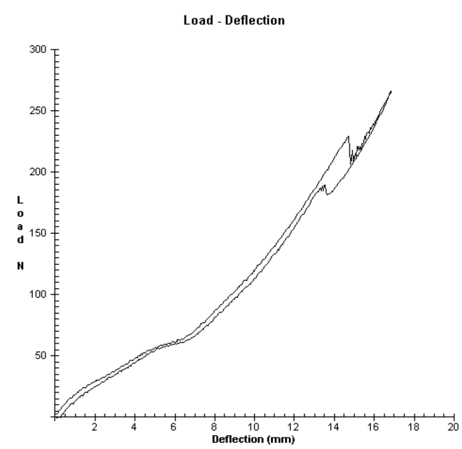
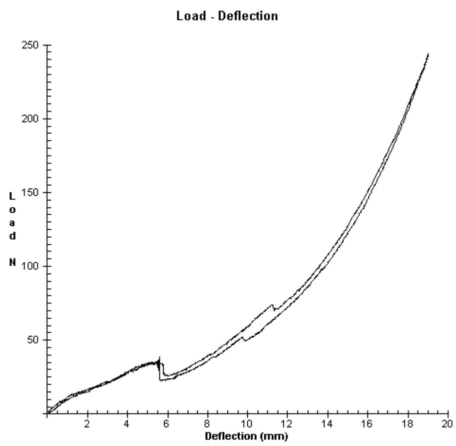
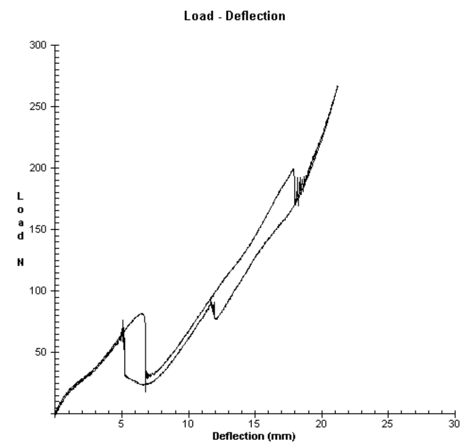


Fig. 10.6.2-4 BH260 0.7 mm

The sensitivity for oil canning is dependent on the design of the door outer panel.





Representative single increment load -- deflection curves from location A.

Fig. 10.6.2-5 DP600, 0.6 mm

Fig. 10.6.2-6 DP600 0.7 mm

The sensitivity for oil canning which was present in the mid-door region is strictly dependent on the design of the door outer panels. In the case of the ULSAC door, it is influenced by the two character lines bordering the mid-door region. The oil canning effect was observed mainly for the DP600 variants caused possibly by residual strains.

10.6.3 Dynamic Dent Resistance Testing

The dynamic dent resistance, as presented in Figure 10.6.3, follows the same trend as the quasi-static dent resistance, but with a higher critical dent load to form a 0.1 mm dent because of the positive strain rate sensitivity of steel.

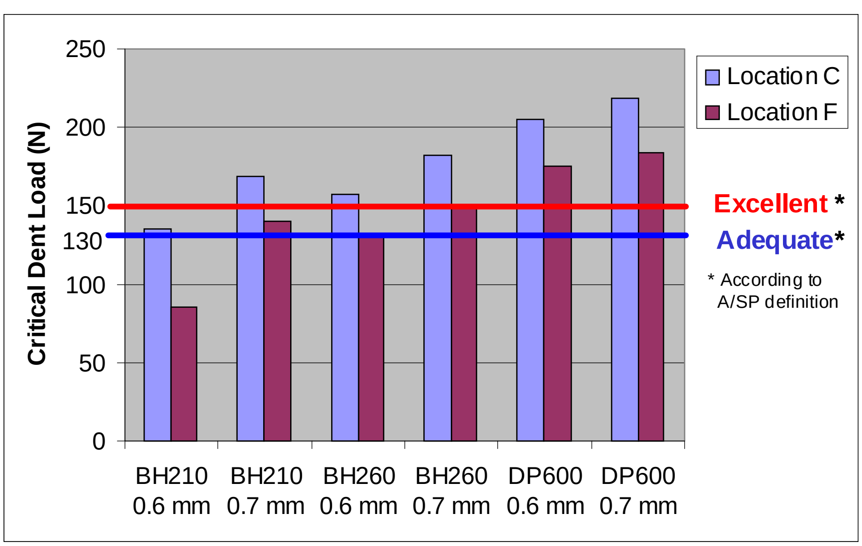


Fig. 10.6.3-1 Critial dent load

Final material selection for ULSAC DH door structure build, was made by experts from the ULSAC Consortium and PES.

The improvement in dent resistance in the mid-door region over the upper region of the door is not as consistent in the dynamic test. By its nature, the dynamic incremental test will not be as dependent on boundary conditions as more local conditions predominate.

10.7 Summary - Dent Testing

Quasi-static, dynamic (three different indenter speeds/energies) and oil canning tests were performed on the ULSAC doors with different material qualities/grades. The ranking of the material grades/thickness in quasi-static and dynamic tests was very similar. Performance of the DP600 was the best, followed by BH260 and BH210. For the oil canning evaluation, which is related more to the specific door styling and curvature of the outer panel than related to material strength, DP600 performed worse than it did in the other tests. The best results for oil canning were achieved by BH260.

Comparing the mechanical properties of the tensile test samples taken from finished doors, there seems to be no explanation for the better performance in dent resistance of the BH260 versus the BH210 because yield and tensile strength is very similar. Contrary to this, all test results have shown advantages for the BH260 quality. Maybe this goes together with the observation of different relaxation behavior concerning the youngs modulus of different steel grades. (Complete test reports are included in the Appendix).

10.8 Final Material Selection for ULSAC DH Door Structure

The final material selection for the ULSAC Front Door Outer Panel was made by a group of experts including steel supplying companies, testing companies, ULSAC program director and PES representatives. All test results were taken into consideration (static and dynamic dent resistance, oil canning sensitivity). Furthermore, appearance of the outer panels was taken as a criterion as well. Due to the fact that the BH260 material in 0.7 mm thickness has shown the best overall performance, the final decision was to choose this material for ULSAC outer panels. All DH is manufactured using this material. It is important to make the remark that this material selection is strictly related to the styling of the ULSAC door and not a general recommendation for door outer panels. Other material grades or thicknesses may offer additional weight saving potential in combination with other styling or other forming technologies.

11 Economic Analysis

Economic Analysis was undertaken to determine the manufacturing cost effectiveness of the ULSAC door structure.

Background

As part of the ULSAC program, an economic analysis was undertaken to determine the manufacturing cost effectiveness of the proposed solution.

The objective of this program was to establish a credible cost estimation of the ULSAC door structure by using automotive practices of manufacturing engineering, process engineering and cost estimating.

To undertake this program, Porsche Engineering Services, Inc. (PES) organized an interactive process between product designers, stamping process engineers, assembly line designers and cost analysts. The team was comprised of the following organizations:

Porsche Engineering Services, Inc. (PES)	Program Management (incl. Validation)
Porsche AG	Cost Estimation
Battelle	Stamping Process Engineering
Classic Design	Assembly Process Engineering
Camanoe Associates / MIT	Cost Analysis

The goal was to allow end users the possibility to analyze "what-if" scenarios and compare existing or potential door structures to the ULSAC door structure. Therefore, the entire program used a technical cost model program developed by Camanoe Associates, a group of researchers of the Massachusetts Institute of Technology (MIT). It is a further development of the cost modeling approach used for the Economic Analysis of the ULSAB Phase 2 Program.

The Technical Cost Model is programmed to allow the user to change any of the general inputs to suit their specific environment or to change specific inputs for alternative processes.

In addition, because the costs shown on the ULSAC cost model reflect only direct factory costs, and are relative to the level of product development as of today, a user may wish to enter additional cost categories. The cost model has been arranged to accommodate this.

Process design means that costs can be analyzed based on exact definitions concerning fabrication and assembly requirements.

Some of the areas not included in the ULSAC Cost Analysis are:

- SQA (Supplier Quality Assurance), quality testing, auditing
- Impact on closure structure through other system developments (i.e. electrical, trim etc…)
- Changes as a result of physical closure structure testing
- Start-up and production launch costs
- Marketing campaigns
- Transportation costs
- Departmental costs, marketing, finance, purchasing, human resources, etc.
- Preparation for paint

11.1 The Process of Cost Estimation

11.1.1 Overview

The ULSAC Economic Analysis began with the establishment of the basic assumptions regarding general inputs.

The program then commenced to establish the estimated production costs against an extremely well defined design. Having a process design meant that costs could be analyzed based on exact definitions concerning fabrication and assembly requirements.

On the parts fabrication side, each stamping and hydroformed component was studied to determine the process. Batelle (for stamping) and Drauz (for hydroformings) provided a proposal for the manufacturing process and the corresponding input data in the model.

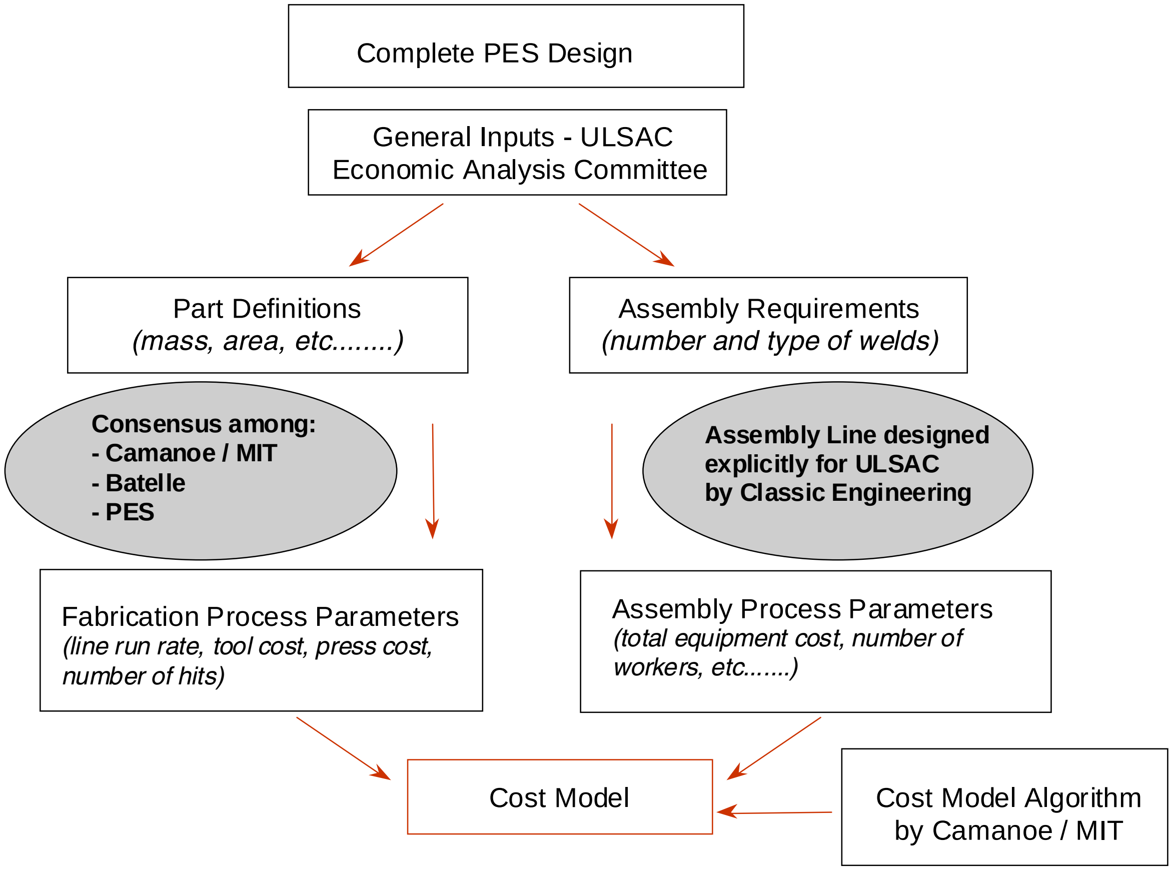


Figure 11.1.1-1 Mechanism for determination of all part inputs

Parallel to that PES, as well as MIT, analyzed the parts to obtain corresponding manufacturing engineering input data. After that, Batelle, MIT and PES compared the proposals to ensure reasonableness and defined the input data used in the cost analysis.

Some parts were assumed to be purchased. This affects either extremely small parts or parts which need no fabrication processes like stamping or hydroforming.

For the assembly line design and processing, PES provided Classic Design with a detailed bill of materials (BOM) and parts sequencing. From this, the door assembly area was developed in a macro view, which established the equipment, tooling, building and manpower required to fulfill the production requirements. Following validation by PES and MIT, this data was then integrated in the cost model by MIT for final cost estimation.

Cost models can be used not only for determining the manufacturing cost of the ULSAC door structure, but also, other alternative designs.

11.1.2 Cost Model Algorithm Development

In this section the methodology for development of the technical cost models is described. The cost models can be used not only for determining manufacturing costs for the ULSAC design, but also for costs associated with alternative designs. The models allow the capability to track the major cost contributors and to determine opportunities for target areas for reduction.

The principal objective for this project includes further development of a cost estimation tool to aid automotive designers specifically interested in costs associated with the ULSAC design. The cost model permits any user to easily adapt various input parameters, allowing cost investigations for alternative designs on a consistent basis.

The cost model must account for various processes used in the manufacture of the door structure, including stamping, hydroforming, sheet-hydroforming and assembly. Based on numerous input parameters, both economic and technical, the model tracks cost contributions to the stamping process from blanking, welding (for tailored welded blanks) and stamping for all parts. Similarly, hydroformed part costs are broken down into contributions from bending, pre-forming, final hydroforming and trimming. The assembly process costs include cost contributions from spot welding, active gas metal arc welding (MAG), laser welding and adhesive bonding.

Technical cost modeling is a technique used by MIT for simulating manufacturing costs. The technique is an extension of conventional process modeling, with particular emphasis on capturing the cost implications of material and process variables and various economic scenarios.

The focus of the technical cost models developed for ULSAC are limited to direct manufacturing cost, although the models could be expanded to include indirect costs and aspects of the entire product life-cycle. Direct manufacturing costs involve specific processes: fabrication and assembly of the door structure. Indirect manufacturing costs, including executive salaries, marketing and sales, shipping and purchasing, research and development, and profits are not considered.

Other costs, which are related to the manufacturing process and mentioned in the introduction of this chapter, are also not considered in the analysis.

Cost is assigned to each unit operation from a process flow diagram. For each of these unit operations, total cost is broken down into separately calculated individual elements.

- *Variable cost elements*: Materials, labor, and energy
- *Fixed cost elements*: Equipment, tooling, building, maintenance and overhead labor

General inputs were established in order to create assembly requirements and fabrication & process parameters.

Developed to breakdown and track contributions from variable and fixed costs, the models identify the major cost contributors to manufacturing. After the direct manufacturing costs are established based on an initial set of input parameters, sensitivity analysis can be performed to indicate the cost impact of changes to key parameters. Technical cost models provide an understanding not only of current costs, but also of how these costs might differ in the face of future technological or economic developments. Typical parameters investigated in regards to sensitivity analyses include: wage, production life, raw material prices and tooling costs.

11.1.3 General Inputs

As stated previously, the Economic Analysis began with the establishment of the general inputs. An example of these inputs is as follows:

General Input	
Annual Production Volume	225,000
Working Days per year	240
Production Location	Mid-West USA
Wage including benefits	$44/h
Interest Rate	12%
Equipment Life	20
Production Life	5
Building Life	25
No. of Shifts	2

Figure 11.1.3-1 General Inputs

The same types of press lines & press parameters were assigned to the ULSAC parts as were used for the ULSAB body structure.

11.1.4 Fabrication Input

For each part in the ULSAC design, a press line time requirement was calculated. The machine clean running rate, the line downtimes, the part reject rates and the total annual production volume are used to determine the total time needed on the line for the given year. For choosing a press line, the same types of lines, and therefore the same line parameters were assigned to the ULSAC parts as were used for the ULSAB body structure in the ULSAB phase 2 program. Therefore, one of the ULSAB press lines was chosen for the stamping process of each ULSAC stamping part. The following tables give an overview over the important tooling and press line parameter for the major ULSAC parts.

Figure 11.1.4-1 Press Line Configuration for ULSAC Stamping

Press Line Configuration	
Press Group	**Capacity**
ULSAB Type A	1600 ton DA/1000 ton SA
ULSAB Type B	1000 ton DA/800 ton SA
ULSAB Type C	800 ton DA/500 ton SA

DA=Double Action, SA=Single Action

Press Line Configuration for Major Parts		
Part ID	**Part Name**	**Press Line**
3000/3001	Panel Front Door Outer	Tandem ULSAB Type A (6 presses)
3004/3005	Panel Front Door Inner Rear	Tandem ULSAB Type C (4 presses)
3008/3009	Panel Front Door Inner Front	Tandem ULSAB Type B (4 presses)
3020/3021	Panel Mirror Flag Outer	Tandem ULSAB Type C (5 presses)

Stamping Process Parameter for Major Parts			
Part ID	**Part Name**	**Tooling**	**Tooling Cost**
3000/3001	Panel Front Door Outer	Single-Att.	(2*) $ 1,200,000
3004/3005	Panel Front Door Inner Rear	Double-Att.	$ 700,000
3008/3009	Panel Front Door Inner Front	Single-Att.	(2*) $ 700,000
3020/3021	Panel Mirror Flag Outer	Double-Att.	$ 650,000

It is assumed that all stamping parts are produced on tandem press

It was assumed that all stamped parts for the ULSAC door structure were produced on tandem press lines.

lines. Sensitivity analysis has shown that there is no significant difference in costs for fabrication of these parts in using either tandem or transfer presses. The lower investment for tandem press lines is nearly compensated by their lower line rate.

A complete layout for the fabrication of the hydroforming parts, including hydroforming presses, was planned by Drauz Umformtechnik. Based on this layout, the manufacturing engineering with the corresponding data for the cost model input was generated and validated by Porsche AG, MIT and Batelle. It is assumed that both hydroformed parts will be produced with double attached tools for RH & LH side.

Figure 11.1.4-2 Hydroforming Press Parameters

Hydroforming Process Parameter			
Part ID	Part Name	Tooling	Tooling Cost*
3012/3013	Front Door Hinge Tube	Double-Att.	$ 1,300,000
3014/3015	Front Door Latch Tube	Double-Att.	$1,100,000

* including the process steps bending, preforming, hydroforming, trimming

11.1.5 Assembly Input

The assembly line was designed explicitly for ULSAC by Classic Engineering and includes equipment & tooling investment, assembly plant area and labor force. Cost estimates concerning material, energy, overhead labor and maintenance were performed by MIT.

It is assumed that the door structure is produced in a plant with the same downtime assumptions concerning ‘no shifts’, ‘worker unpaid’ and ‘paid downtime’ as in the assembly of the ULSAB body structure. Due to the fact that Classic Design defined the net line rate of the door assembly with 58.59 jobs per hour (jph), nearly 4 jph slower than the ULSAB line rate, a door assembly overtime is needed and defined to produce the same 225,000 units per year.

The model addresses the costs associated with stampings, tailor welded blanks, tubular hydroformings, and purchased parts.

11.2 Cost Model Description

11.2.1 General

The following chapter describes the salient information and input parameters of the ULSAC technical cost model.

A model was constructed to estimate the economics of each part fabrication and assembly process which would be utilized in the manufacturing of either the ULSAC or the "state of the art" generic door design. The model addresses the costs associated with stamping, tailored blanked parts, tubular and sheet hydroforming and purchased parts for the part fabrication. With regard to assembly, the model estimates costs associated with several different welding processes (laser, spot and MAG welding) as well as adhesive bonding, mechanical fastening and hemming.

To a large extent, the model design was based on the existing ULSAB Phase 2 Cost Model, but with some important modifications, both in terms of functionality and user-friendliness. With regard to user-friendliness, the model has been reorganized to more easily represent the different processing techniques employed in the manufacture of the doors in question. As a result, the various "sheets" of the model have been reorganized according to the various process steps rather than the level of cost estimation detail desired.

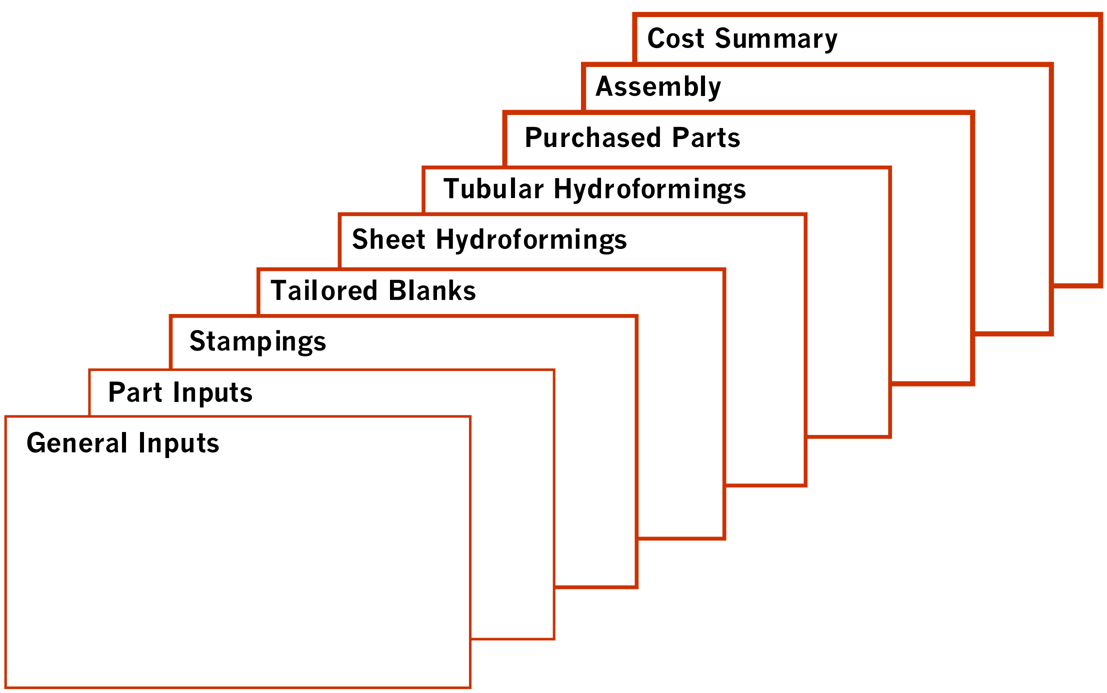


Figure 11.2.1-1 Technical Cost Model Layout

Tailor welded blank costs are calculated directly from each individual blank, rather than a weighted average.

The ULSAC technical cost model consists of nine different model sheets, the first two contain model inputs, the next six address the various manufacturing processes (including assembly), and the final sheet provides an overall cost summary. This organization allows the user to easily address the issues in any single processing technique simply by selecting the relevant model sheet.

In order of appearance, these sheets are: General Inputs, Parts Inputs, Stamping, Tailored Blanks, Sheet Hydroforming, Tubular Hydroforming, Purchased Parts, Assembly and Cost Summary.

In terms of functionality there have been numerous model changes to address limitations in the previous ULSAB model. These improvements come in four areas; tailored blanked parts, tubular hydroforming, sheet hydroforming and assembly. Each improvement came about as the result of some limitation on the analysis imposed by the previous ULSAB phase 2 model structure.

In the following, the approach of the ULSAC cost model will be explained in more detail for the processes 'Tailored Welded Blanks', 'Tubular Hydroforming' and 'Assembly'.

11.2.2 Tailored Welded Blanks

The major change to the cost modeling of tailored welded blank parts has to do with the calculation of the cost of materials. In the case of ULSAB, tailored blanks were treated like any other stamped parts except they were considered to have a very special input regarding blank size and weight. The geometric requirements of each constituent blank were used to arrive at a total weight of the tailored blank, as well as a weighted average cost of the material. Thereafter, the part was treated as an ordinary stamping plus considering the welding process.

The limitation of this approach was that the user had to know the weighted average cost of the material which of course was part specific (unlike all other material costs which were only material type specific).

The new ULSAC model remedies this situation by calculating the material costs directly from each individual blank rather than using a weighted average. The resulting cost is identical, but the method for arriving at the cost is more transparent and eliminates the need for the user to do additional calculations outside of the model itself.

Tubular hydroforming costs are calculated in four sub-process steps: bending, pre-forming, hydroforming and trimming.

11.2.3 Tubular Hydroforming

There are minor changes to the tubular hydroforming cost estimations with regard to the breakdown of subprocess steps. Both the original ULSAB and the new ULSAC models consider four subprocess steps; bending, pre-forming, hydroforming and trimming. However, in the ULSAB model, the costs for these processes were calculated together.

Due to the limited use of tubular hydroforming in the ULSAB program, it was not considered important to be able to address the costs of each of the four subprocess steps individually.

In the ULSAC model, this has changed. The model now uses the individual inputs for each subprocess step to arrive at a detailed cost breakdown. The results using the two models should remain unchanged, provided that the inputs are consistent, however, the ULSAC model allows the user more freedom with regard to the model inputs.

11.2.4 Assembly

The assembly portion of the model has experienced the most change from the previous ULSAB model. This was required to remedy a very important limitation imposed by the structure of the ULSAB model, in particular the need to be able to generate cost estimates at varying levels of production volume.

The original ULSAB model was designed to provide a cost estimate for assembly based on extensive knowledge about the assembly line on the part of the user. The model essentially required the user to first have a complete description of the assembly line including all levels of investment in equipment and tools, levels of manpower and the number of assembly stations. The model was intentionally designed in this way because Classic Design was contracted to supply all of the details of the assembly line. The limitation arose when it was decided that an analysis of the costs at a production volume other than that used by Classic Design was desired. The assembly line design was only appropriate at the 225,000 parts per year production volume used by Classic Engineering. The model had no mechanism for adjusting these investments at other production volumes.

Once the appropriate number of assembly stations is determined, the model can respond to changes in production volume..

The assembly portion of the ULSAC model was constructed to overcome this serious limitation. The idea behind the new model was that the user should not have to specify all of the details of the line at every production volume. Instead the user would specify the assembly "effort" required, measured in terms of time to perform the various assembly operations. At any production volume level, a cycle time for the process is determined and the assembly "effort" is compared with this cycle time to determine the number of stations required for each assembly operation. Once the appropriate number of stations is determined, average levels of manpower, equipment and tooling investments, etc. could be applied to determine the overall costs.

By employing this approach, the model can respond to changes in production volume. For example, at lower production volumes, the cycle time is higher and thus the number of stations required to accomplish the required assembly is reduced. As a result, all of the investments and manpower requirements are also reduced basically providing a modified assembly line description which can then be used to determine the per vehicle assembly costs. Of course, this approach is just an estimation of how costs change with changing production volumes. In practice the issue is far more complicated, and involves complex considerations of line balancing to minimize the investment and labor requirements for any set of operations while still remaining within the limits imposed by precedence (the need to assembly some parts before others can be added). Nonetheless, this mechanism provides a reasonable and consistent method for allowing the assembly line to scale with production volume.

To ensure that the ULSAC assembly model gives results consistent with the method used in the older ULSAB model, a series of overrides concerning the levels of investment and time requirements was implemented. The user must be sure to input the proper baseline investment costs (in equipment and tooling) per station for each assembly operation, as well as the appropriate assembly time requirement (an appropriate time requirement is one which results in the correct specified number of stations).

In consequence, results in the model for the annual production volume of 225,000 units are based on an exact assembly planning of Classic Design. Changing this volume in the model, will show tendencies in the cost behavior with the restriction that these costs have not the same quality in accuracy as in the basis assumption of 225,000 units.

The manufacturing costs for a pair of ULSAC door structures (mass = 21.9 kg, 34 parts) is calculated at $133.

11.3 ULSAC Cost Results

11.3.1. Overall Cost Results

The cost analysis for the ULSAC design is presented, including a breakdown of costs by processes, factor elements and investments. Sensitivity analyses are included to provide examples of what parameters may affect the costs of the door.

The manufacturing costs for a pair of ULSAC door structures with a calculated mass of 21.9 kg and 34 parts (17 parts per side) result in an overall value of $133 per door pair.

These costs can be broken down into $79 from parts fabrication and $54 from assembly.

	ULSAC LH & RH Door	
Parts Fabrication	**$78.77**	**59.3%**
Stampings	$30.74	23.1%
Tailored Blank Stampings	17.41	13.1%
Tubular Hydroformings	21.50	16.2%
Purchased Parts	9.14	6.9%
Assembly	**$53.97**	**40.7%**
Total Cost of Pair of Doors	**$132.75**	**100.0%**

Figure 11.3.1-1 Overall Cost Results

Parts fabrication can be broken down further into the different processes (e.g. stamping, tailored blanks, etc...).

11.3.2 Cost Breakdown for Fabrication

The parts fabrication total can be further broken down into the different processes stamping, tailored blank stamping, tubular hydroforming, and purchased parts.

The following two tables show these costs broken down either in subprocesses and also in variable and fixed costs, which are further broken down into their individual cost elements.

ULSAC LH&RH Door Parts Fabrication Cost Breakdown by Individual Process Step		
Stampings (total)		**$30.74**
	Material	$16.10
	Blanking	0.55
	Stamping	14.08
Tailored Blank Stampings (total)		**$17.41**
	Material	$5.51
	Blanking	0.48
	Welding	5.95
	Stamping	5.47
Tubular Hydroforming (total)		**$21.50**
	Material	$6.39
	Bending	2.93
	Preforming	2.93
	Hydroforming	7.83
	Trimming	1.41
Purchased Parts (total)		**$9.14**
Parts Fabrication total		**$78.79**

Figure 11.3.2-1 Part Fabrication Costs Breakdown by Process Step

Nearly 40% of parts fabrication cost were needed for stamping parts, the other 60% was needed for modern technologies.

Nearly 40% of total parts fabrication costs is needed for stamping parts. The remaining 60% are needed for modern technologies like tailored welded blanks and hydroforming.

The primary driver for the stamped parts is material with the result that nearly half of the part costs come from material. Due to the stage of program development, a very cautious approach was taken in determining blank sizes.

For tubular hydroforming, the percentage of material is smaller although the welding process of the tubes is included in material costs. Reasons for that can be found in lower material costs due to a higher material utilization in tubes which leads to less scrap and in the highest percentage in fixed costs due to the lower cycle time.

ULSAC LH & RH Door	Cost Breakdown					
	Stampings		Tailored Welded Blank Stampings		Tubular Hydroformings	
Material Cost	$16.10		$5.51		$6.39	
Labor Cost	1.91		1.75		1.88	
Energy Cost	0.73		0.79		0.68	
Total Variable Costs	**$18.74**	**61%**	**$8.05**	**46%**	**$8.95**	**42%**
Equipment Cost	$4.82		$4.99		$5.10	
Tooling Cost	4.75		1.73		2.96	
Building Cost	0.18		0.32		0.45	
Overhead Cost	1.28		1.62		3.19	
Maintenance Cost	0.97		0.70		0.85	
Total Fixed Costs	**$12.00**	**39%**	**$9.36**	**54%**	**$12.55**	**58%**
Total Cost	**$30.74**		**$17.41**		**$21.50**	

11.3.2-2 Cost Breakdown - Process Steps

Roughly 40% of the door structure costs are assembly costs which aer dominated through fixed costs of 75%.

11.3.3 Cost Breakdown for Assembly

Roughly 40% of the door structure costs are assembly costs, 75% of which are attributed to fixed costs. High automation due to the defined annual production volume leads to high investment costs.

ULSAC LH & RH Door Assembly	
Material Cost	$0.27
Labor Cost	11.26
Energy Cost	2.19
Total Variable Costs	**$13.72**
Equipment Cost	$12.45
Tooling Cost	8.69
Building Cost	1.53
Overhead Cost	15.31
Maintenance Cost	2.27
Total Fixed Costs	**$40.25**
Total Cost	**$53.97**

11.3.3-1 Cost Breakdown for Assembly

Wage, interest rate and the material price are important parameters which influence the results.

11.3.4 Sensitivity Analysis

An important element of the technical cost modeling approach is to determine the potential cost movements as a result of sensitivity analysis and other scenarios that could impact cost.

Areas investigated in the following table are labor wage, production life, equipment life, interest rate, unplanned downtime for stamping and material prices.

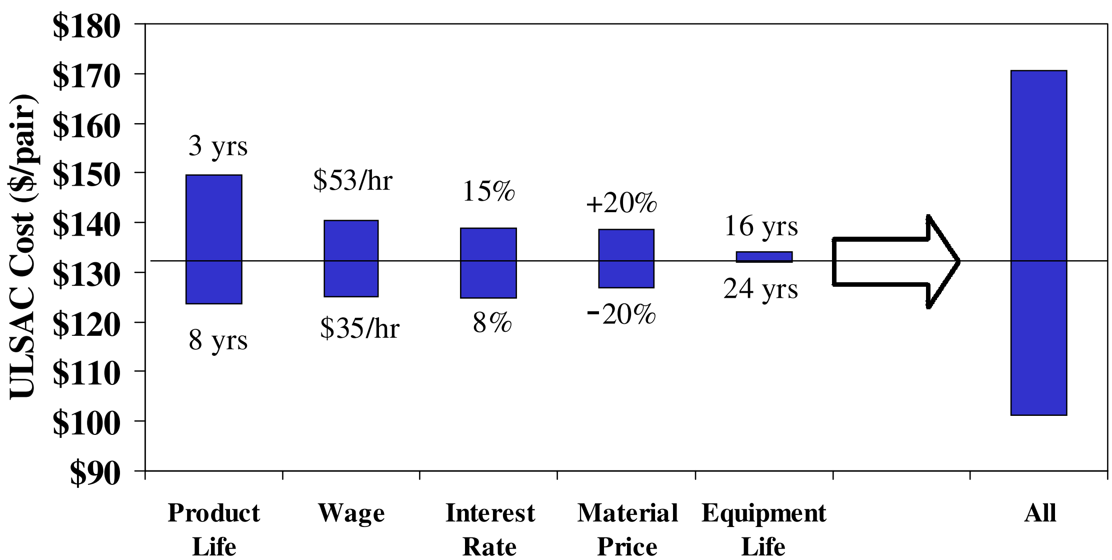


Figure 11.3.4-1 Sensitivity Analysis

Results show that wage, interest rate and the material price are important parameters which influence the results in a way that can not be neglected. As for the ULSAB body structure, the most sensitive parameter for ULSAC is the production life because the tooling costs have to be depreciated in that time period. Parameters like energy and building unit cost, as well as the equipment life do not influence the total costs.

The ULSAC Latch Tube had to be pre-bent, pre-formed and finally, fully hydroformed in the hydroforming tool.

11.4 Case Study of a 'state-of-the-art'-generic door structure

11.4.1 Description of the generic door design approach

Three doors, all frameless and considered state-of-the-art, were procured for benchmarking purposes.

To develop an initial generic door shell, average sizes and shapes of the doors were determined based on digitized exterior dimensions. Using CAD, the shells were proportionally scaled to fit a 3-dimensional box, equivalent to that which the ULSAC door would fit.

Criteria was then established, based on similarities in design applications and processes between the three doors, such as the use of reinforcements and welding processes. Assembly and manufacturing process such as, tubular hydroformed parts and laser welding were not included in the generic door design. However, a laser welded blank for the door inner panel, was included. Conventional considerations were given to the design, manufacture and processing of all parts.

Material thickness of the generic door parts was based on the material thickness with comparable applications of parts within the three benchmarked doors. Using the CAD system analysis software, the mass of all parts was subsequently analyzed and documented.

Figure 11.4.1-1
Generic Door Panel Door Outer

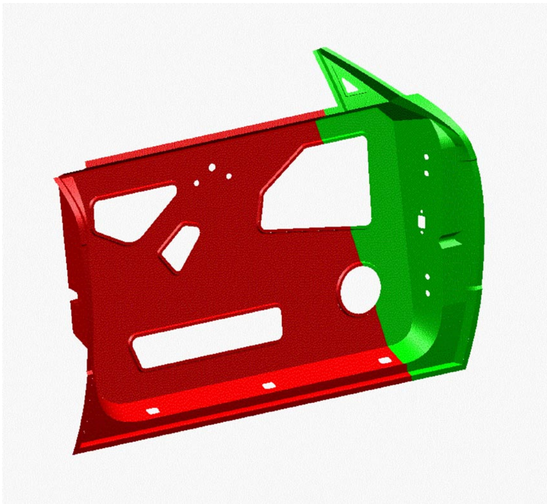


Figure 11.4.1-2
Generic Door Panel Door Inner

The two major parts of the generic door are the Panel Door Outer and the Panel Door Inner which is designed as a TWB.

The two major parts of the generic door are the Panel Door Outer and the Panel Door Inner which is designed as a tailor welded blank. The generic door structure, shown in Figure 11.5.1-3 was comprised of the following parts (Figure 11.5.1-4).

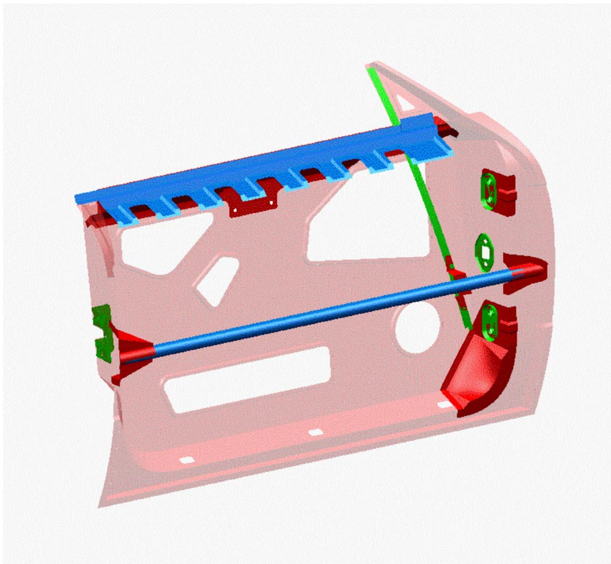


Figure 11.4.1-3 Generic Door Structure Detail Design

State of the Art'-Generic Door		
Parts Number	Parts Name	Mass [kg]
3500-01	Panel Outer	4.773
3500-02	Panel Inner	7.528
3500-03	Reinforcement Belt Outer	0.629
3500-04	Reinforcement Belt Inner	1.574
3500-05	Reinforcement Hinge Upper	0.113
3500-06	Reinforcement Hinge Lower	0.437
3500-07	Reinforcement Latch	0.061
3500-08	Side Intrusion Beam	1.183
3500-09	Bracket Side Intrusion Beam Front	0.112
3500-10	Bracket Side Intrusion Beam Rear	0.196
3500-11	Tapping Plate Hinge (2X)	0.141
3500-12	Channel Glass Guide	0.167
3500-13	Bracket Channel Glass Guide	0.027
3500-14	Reinforcement Check Arm	0.044
	TOTAL	16.985

Figure 11.4.1-4 Generic Door Parts List

Manufacturing process proposals and assembly system data was estimated for input data on the Cost Model.

11.4.2 Estimation of input data

For the analysis of the parts fabrication, Porsche Engineering Services provided component data to Batelle, MIT and Porsche in Germany, who worked out manufacturing process proposals for each part. These proposals included tooling costs, press requirements, manpower, run rates and blank sizes. This data was then reviewed by Porsche, MIT and Batelle to establish the optimum process per component. This methodology was nearly similar to ULSAC.

Concerning assembly, Classic Design provided the assembly system data based on the product information supplied by Porsche Engineering Services. Unlike ULSAC, where Classic undertook a detailed macro study, the process for the generic door was established by Classic analyzing the major assemblies and then utilizing their vast experience, to determine the equipment, tooling, manpower and space requirements for achieving production volumes. All trim attachments were identical to ULSAC and therefore these particular assembly processes were the same.

11.4.3 Overview of major assumptions

	ULSAC LH & RH Door		State of the Art Generic Door LH & RH Door	
Parts Fabrication	No. of parts	Calculated Mass [kg]	No. of parts	Calculated Mass [kg]
Ordinary Stampings	8	11.678	12	15.442
Tailored Welded Blanks	2	2.472	2	15.056
Tubular Hydroformings	4	2.79	-	-
Purchased Parts	20	4.912	16	3.474
Overall	**34**	**21.852**	**30**	**33.972**
Material Utilization (Stampings)	51%		48%	
Material Utilization (Hydroformings)	71%		-	
Assembly				
Direct Labor	14		16	
Indirect Labor	20		21	
Number of Spot Welds	36		142	
Length of Laser Welds [mm]	4.246		0	
Length of MAG Welds [mm]	1.852		1,676	
Length of Adhesive [mm]	4.988		7,220	
Number of Robots	26		28	
Number of Assembly Stations	46		36	

Figure 11.4.3-1 Major Assumptions

Comparing the two door structures shows that material costs are much lower for ULSAC.

11.4.4. Overall Results

	ULSAC LH & RH Door		State of the Art Generic Door LH & RH Door	
Parts Fabrication	**$79.00**	**60.7%**	**$91.00**	**66.6%**
Material	$28.00	21.5%	$48.00	35.0%
Stampings (without material)	15.00	11.3%	16.00	11.5%
Tailored Blank Stampings (without material)	12.00	9.2%	20.00	14.5%
Tubular Hydroformings (without material)	15.00	11.6%	0.00	0.0%
Purchased Parts	9.00	7.1%	7.00	5.1%
Assembly	**$54.00**	**40.7%**	**$47.00**	**33.4%**
Total Cost of Pair of Doors	**$133.00**	**101.3%**	**$138.00**	**100.0%**

Figure 11.4.4-1 Overall Results

The total costs of the generic door are very close to the ULSAC door. However, they are broken down in a different way. The higher amount in investments for modern technologies and partly higher cycle times (tubular hydroforming) for ULSAC can be compensated with extremely lower material costs.

These savings in material costs are based on higher material utilization (mainly due to the use of tubes) and on large weight savings in the door structure and the associated material input.

Both door structures - ULSAC and the generic door - will cost approximately the same amount.

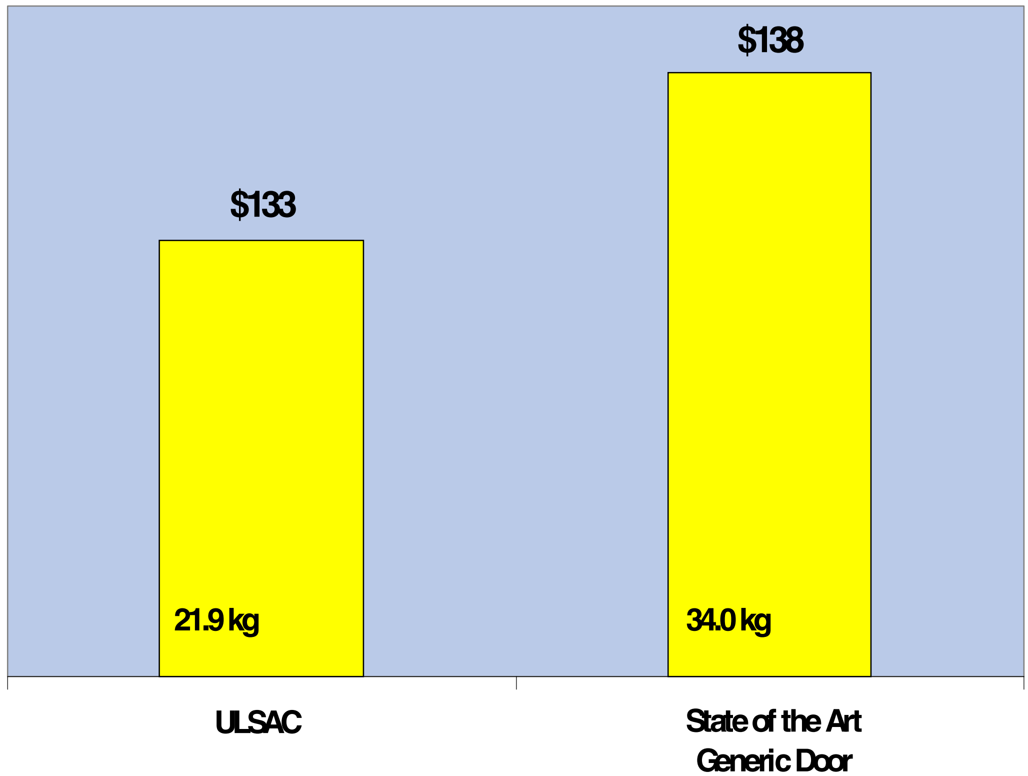


Figure 11.4.4-2 Comparison of ULSAC door structure and Generic door structure

The difference of the two results is smaller than the recognized level of variance which can generally be considered for a calculated cost estimate. With that it can be stated that both door structures will cost approximately the same.

11.5. Conclusion

The results of the economic analysis of the ULSAC program show that a door structure with enormous weight savings and a comparable performance to state of the art generic doors can be built without cost penalty.

This result is similar to that of the ULSAB program which was presented two years ago.

Additional costs for innovative processes and technologies like hydroforming or laser welding can be compensated through enormous savings in material costs.

12 Summary of Results

Summary of Validation Phase Results

The goal of the ULSAC Program has been achieved with the ULSAC DH Door Structure build and tested in the Validation Phase. The normalized mass value of the ULSAC DH door structure at 13.27 kg/m^2 is significantly below the target of 15.50 kg/m^2. Compared to benchmarked door structures, the ULSAC door structure achieved a mass reduction for an average normalized mass [M_N] in the range of 30% to 42%.

The target for Vertical Door Sag stiffness, which was based on data gathered from OEM surveys, was not reached. Benchmarking of frameless doors tested under same conditions as the ULSAC DH Door Structure shows, that the ULSAC Door Structure performs very similar at significantly reduced mass (see Figure 12-1).

	ULSAC DH	ULSAC Concept Phase Target	Door A	Door B	Door C
Vertical Door Sag Stiffness N/mm	157	287	109	194	497
Normalized Mass M^N kg/m_2	13.27	15.5	24.94	19.7	24.36

Figure 12-1 Vertical door sag stiffness

The levels of Upper and Lower Lateral Stiffness are above the Concept Phase targets and state-of-the-art compared to the benchmarked frameless doors (see Figure 12-2).

Loadcase	ULSAC DH	ULSAC Concept Phase Target	Door A	Door B	Door C
Upper Lateral Stiffness Nm/deg	259	127	352	197	188
Lower Lateral Stiffness Nm/deg	261	48	467	309	188

Figure 12-2 Upper and lower lateral stiffness

With regards to safety the ULSAC DH Door Structure shows that the design with the two intrusion beams achieves good crush performance compared to benchmarked frameless doors and FMVSS 214 requirements (see Figure 12-3).

	ULSAC DH	FMVSS 214	Door A	Door B	Door C
Initial Crush Resistance at 6" (kN) *	**8.18**	≥ 10.01	8.55	6.18	7.33
Intermediate Crush Resistance at 12" (kN) *	**11.51**	≥ 15.57	7.73	11.21	13.33
Peak Crush Force (kN)	**38.90**	≥ 31.14	15.17	25.56	24.59

* Average Force

Figure 12-3 Quasi-static side intrusion

The longitudinal door crush analysis results show that the ULSAC DH door structure would considerably contribute to enhance a vehicles crash performance in frontal crashes.

The design was focused on mass reduction and CAE analysis was used to predict the structural performances of the actual ULSAC DH door structure. Generally, the analysis results correlated well with the test results (see Figure 12-4).

Structural Performance	ULSAC Validation CAE Analysis Results	ULSAC Concept Phase Target	ULSAC DH Test Results
Upper Lateral Stiffness Nm/deg	**245**	127	259
Lower Lateral Stiffness Nm/deg	**250**	48	261

Figure 12-4 Upper and lower lateral stiffness CAE correlation

The analysis of the door sag stiffness over-predicted the performance compared to the actual test results. Additional correlation analysis, using the build specification and actual part material thickness' show the results in a close range to the test results (see Figure 12-5)

Performance	Correlation Analysis Results	DH Test Results
Vertical Sag Stiffness (N/mm)	169	157
Mass DH Door Structure (Kg)	10.47	10.47

Figure 12-5 Vertical sag stiffness CAE correlation

The ULSAC door structure shows good intrusion performance in the analysis with levels close to FMVSS 214 requirements, especially for the initial crush resistance, which is normally the most difficult target to achieve. The results correlate in an acceptable range with the test results (see Figure 12-6 and Figure 12-7).

Criterion	FMVSS 214 Requirements	ULSAC DH Test Results	ULSAC CAE Analysis Results
Initial Crush Resistance	≥ 10.1 kN	8.18 kN	8.53 kN
Intermediate Crush Resistance	≥ 15.57 kN	11.51 kN	14.92 kN
Peak Crush Resistance	≥ 31.14 kN	38.9 kN	41.66 kN

Figure 12-6 Quasi-static side intrusion CAE correlation

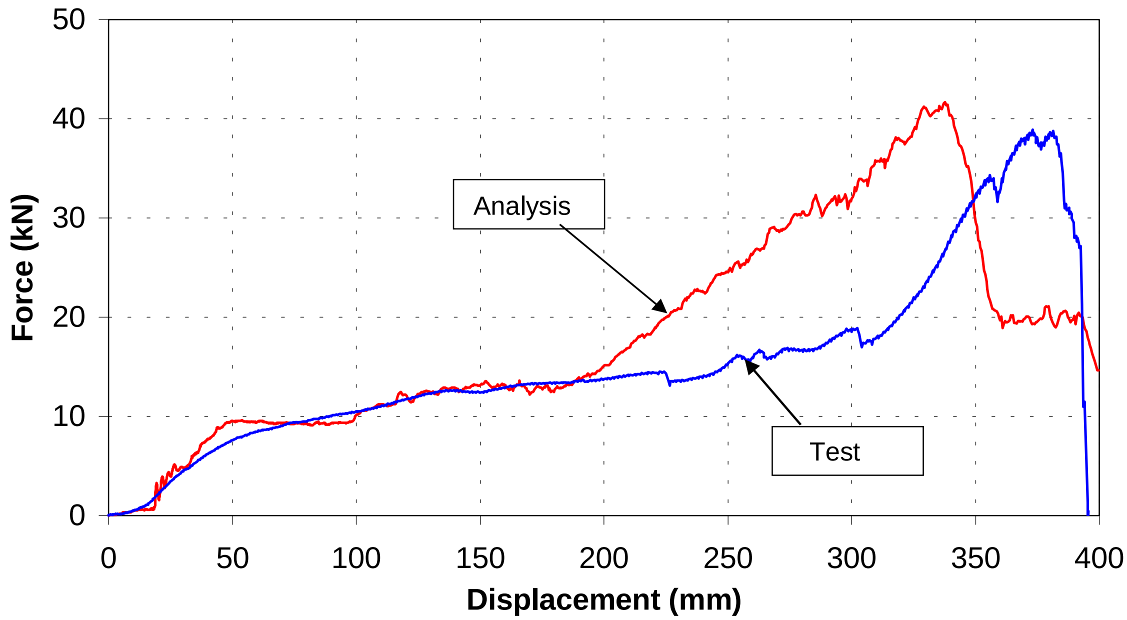


Figure 12-7 Force versus displacement CAE correlation

All parts were feasible to manufacture with material grades and thickness' as specified in the design. For the parts manufacturing, the best-suited material types were selected, together with the ULSAC Consortium.

Forming simulations for the tubular hydroformed parts were performed in parallel to the tool and parts manufacturing. The incremental forming simulation correlated with the actual parts, and shows that this type of simulation is a useful tool, and can be used for future development of tubular hydroformed parts, prior to tool and parts manufacturing.

Testing for dent resistance and oil canning was performed by ULSAC Consortium member steel companies. The results were used to select out of three pre-selected possible materials for the Door Outer Panel manufacturing.

Porsche AG's R&D Center used state-of-the-art joining technologies such as laserwelding and assembly for the build of the ULSAC DH Door Structure.

The ULSAC Cost Analysis has established that two (2) ULSAC DH door structures would cost $133.00 to manufacture and show, compared to a state-of-the-art generic door structure, that mass reduction for automotive closures is achieveable at no cost penalty.

In the Concept Phase, further mass reduction by manufacturing the Panel Front Door Outer at a lower gauge, utilizing the sheet hydroforming process for gaining stretch in the middle area of the panel to enhance dent resistance and oil canning, was discussed as a possible solution.

In respect to sheet hydroforming, as of today, no car manufacturer has a door panel in production, utilizing this manufacturing process. The theoretical advantages, as already mentioned, are not, and could not be proven as of yet. Sheet hydroforming process application is currently in development. Its utilization for the manufacturing of Door Outer Panels is restricted by the requirement of height tonnage presses, which are needed to form tight radii and feature lines, also found on most Door Outer Panels currently in production. The ULSAC Program continues to investigate the opportunity to further reduce the mass of the ULSAC DH door structure with the utilization of the active sheet hydroforming process. The results of this work in progress, will be published in a subsequent amendment to this ULSAC Engineering Report.

Mass reduction with closures, using steel as the material of choice, has reached new levels of achievement with the ULSAC DH door structure design. Further improvements can only be achieved through new steel materials and, not yet mass production feasible, technologies such as tailored tubing and sheet hydroforming.

From a total vehicle view, closures are considered modules, and therefore, targets for substitution with alternative materials to achieve structure mass reduction. So far, Automotive Manufacturers globally, are challenged to provide individual transportation at an affordable price. Therefore, the result of the ULSAC Program, showing that mass reduction with steel closure structures, can be achieved with no cost penalty, is remarkable.